

THE 1975 AND 1976 OPERATIONAL ZOOPLANKTON INVESTIGATIONS
RELATIVE TO THE DONALD C. COOK NUCLEAR POWER PLANT,
WITH TESTS FOR PLANT EFFECTS (1971-1976)

Marlene S. Evans

Thomas E. Wurster

Bethany E. Hawkins

Under contract with:
American Electric Power Service Corporation
Indiana & Michigan Electric Company

Special Report Number 64
of the
Great Lakes Research Division
University of Michigan
Ann Arbor, Michigan
1978

ABSTRACT

This report contains the results of investigations conducted in 1975 and 1976 evaluating the impact of the Donald C. Cook Nuclear Power Plant on the zooplankton of southeastern Lake Michigan. Both the immediate effects of condenser passage and the effects of thermal effluents in the lake were investigated. Only Unit 1 of the power plant was operational in 1975 and 1976.

Temperature and Secchi disc depths were measured during fourteen monthly surveys (April to October 1975 and 1976) and one December (1975) survey. While water temperatures were basically similar in the two years, some differences did occur, particularly in the spring. Water temperatures were a few Centigrade degrees higher in April, May, and June of 1976 than in the previous year. Differences in water temperature at the times of the April cruises were apparently part of a several week trend and were influenced by weather variability. Autumn vertical mixing of the water column occurred one to two months earlier in 1976 than in 1975.

The thermal plume ($\Delta T 0.5 C^{\circ}$) was limited to a comparatively small area ($<3 km^2$) of the survey grid ($250 km^2$). Condenser-passed water was diluted in minutes in the vicinity of the discharge jets to 30% of original concentration by mixing with lake water. This mixing aided in the rapid cooling of condenser-passed water.

Secchi disc depths exhibited the same overall seasonal and temporal patterns in 1975 and 1976 as in the preoperational years. However, transparencies were somewhat less over the survey grid in 1976 than in 1975. There was no evidence of decreased transparencies in the thermal plume.

Monthly survey cruises conducted in 1975 (April to October, December) and 1976 (April to October) provided information on zooplankton distributions over the $250 km^2$ area of the survey grid during plant operation. No evidence of gross alterations in zooplankton populations in the vicinity of the thermal plume was found during any of the 15 cruises. An improved method for estimating zooplankton standing stock ($mg \text{ dry wt.}/m^3$) was developed.

Variations in zooplankton distributions over the survey grid were investigated by using principal component analysis. Depth was identified as the most important factor in the overall abundance patterns of zooplankton. The major survey grid consisting of 30 stations and sampled during April, July, and October of each year was divided into three depth-related regions - an inshore region between the 5 and 10-m depth contours, a middle region between the 10 and 20-m depth contours, and an offshore region extending to the 45-m depth contour. A series of stations between the 1 and 2-m depth contours was sampled during some of the major survey cruises and formed a fourth group differing in community structure from the inshore-middle offshore complex. During the warmer months of the year, zooplankton tended to be least abundant in the inshore region and to increase

in abundance out to the 20 or 30-m depth contour; beyond this point, densities leveled off or decreased slightly. The reverse pattern was observed in the winter (December 1975 short survey).

To compare zooplankton preoperational and operational densities, the survey grid was further divided into eight zones. The inshore and middle regions were each divided into three zones - a plume zone extending 1.6 km north and south of the plant site, and a north and south control zone. The offshore region was subdivided into an inner offshore zone (between the 20 and 30-m depth contours) and an outer offshore zone (between the 30 and 45-m depth contours).

Within the inshore plume zone, the seasonal patterns of abundance of the major taxa were generally similar to one another in the preoperational and operational years, although the cycles of Eurytemora affinis and some cladocerans appeared to be advanced by one month in 1976. These differences were also evident in other zones of the survey grid and were thus not limited to the thermal plume.

Comparisons of zooplankton densities between the preoperational (1971-1974) and operational (1975, 1976) years by major survey month (April, July, October) and by zone (a total of eight) revealed that many taxa occurred in significantly different concentrations before and during plant operation. While differences were detected more frequently in the inshore and middle plume zones than in the six control zones, differences of similar magnitude were observed both in the control and plume zones. The preoperational and operational differences in zooplankton densities appear to represent year-to-year variations in population density with no relationship to plant operation.

Zooplankton mortalities were low and similar in most months (February 1975 to December 1976) averaging 11.8% in the intake forebay and 12.0% in the discharge forebay at the time of sample collection. Mortalities tended to be higher, approaching 50%, during storms and recirculation. Discharge mortalities were generally not significantly higher than intake mortalities except for a few calanoid taxa. There was no evidence of delayed damage due to condenser passage.

Thousands of zooplankton passed through the power plant each second. The estimated biomass of zooplankton entrained each month varied from 229 to 8485 kg dry weight. The upper limit for biomass loss of zooplankton due to condenser passage varied from 11 to 1345 kg dry wt./month. These calculations assumed that mortality in the discharge forebay represented the upper mortality limit.

The average area over which 96% of the zooplankton killed during condenser passage were assumed to first settle out of the water column to the sediments was estimated at 2.2 km^2 . An estimated depositional rate of 6.1 mg

dry wt./ m^2 /day was calculated (using the discharge mortality estimate as the upper limit of zooplankton mortality due to plant passage). This deposition rate was only 0.1% of estimated natural rates (2 to 4 gm/ m^2 /day). Much of the detrital material settling out of the water column in the vicinity of the discharge structures is redistributed to other areas of the lake.

Epibenthic and benthic copepods and cladocerans appeared to be more abundant in the cooling waters in 1976 than in 1975. These taxa may be increasing in abundance because of habitat alterations in the vicinity of the intake structures.

An intensive study mapped zooplankton distributions adjacent to and within the 1-m thermal plume in September 1976. Large increases in zooplankton populations were observed in the 1-m plume. These increases persisted up to several hundred meters from the discharge for certain zooplankton taxa. Vertical displacement of zooplankton over the discharge jets was identified as the most significant factor producing these patterns while dilution and factors contributing to zooplankton patchiness determined the areal extent of the patterns.

This report interrelates the results of the several zooplankton studies conducted at the Donald C. Cook Nuclear Power Plant in 1975 and 1976 and provides an overview of the effects of plant operation on a 250 km^2 area of southeastern Lake Michigan. Some of the limitations of our monitoring program are discussed and suggestions are made of areas which require further investigations.

ACKNOWLEDGEMENTS

The contributions of Nancy Auer, Karen Cumminskey, John Hartig, Judy Odenheimer, Mohammed Omair, and Daniel Sell in collecting and processing the zooplankton samples are gratefully acknowledged. Valerie Smith and Nancy Auer prepared most of the final figures which appear in this report.

Computer programmers Ann Amundsen and Jeanne Harris greatly assisted in the design and maintenance of our data processing system. Dorothy Mohler provided excellent keypunching services. Edward Johnston provided advice on statistical analyses.

Captain Edward Dunster and First Mate Earl Wilson of the R/V MYSIS went out of their way many times in unfavorable weather conditions to allow the successful completion of the cruises. Their cooperation during all the aspects of our surveys was much appreciated. Thanks are extended to the members of the benthos laboratory who participated in the cruises. Frank Tesar, John Dorr, and others in the fish laboratory assisted with small boat operations.

William Yocum deserves special thanks for designing the plume sampling equipment and for assisting in the field. Tom Kriesal and Jon Barnes provided special navigation equipment for the plume study and have always been helpful during field operations. Mark Weisham worked tirelessly on the electronic-bathythermograph which was used on the survey cruises.

John Ayers, Edward Johnston, Sam Mozley, and Ronald Rossmann reviewed the manuscript and made valuable suggestions for improvement. Steve Schneider also deserves thanks for editorial comments.

Finally, John Ayers, Erwin Seibel, and Ronald Rossmann deserve special thanks for overall encouragement and assistance.

CONTENTS

	<u>Page</u>
ABSTRACT	iii
ACKNOWLEDGEMENTS	vi
LIST OF FIGURES	x
LIST OF TABLES	xv
INTRODUCTION	1
 SECTION 1. THE SEASONAL AND SPATIAL DISTRIBUTIONS OF ZOOPLANKTON DURING THE 1975 AND 1976 SURVEY CRUISES	
INTRODUCTION	4
MATERIALS AND METHODS	5
The Survey Grid	5
Physical Measurements.	7
Zooplankton Sampling Methods	8
Counting Techniques.	8
Dry Weight Determinations.	8
Principal Component Analyses	9
RESULTS	10
Water Temperatures	10
Secchi Disc Depths	18
Comparison of Old and New Methods for Determining Zooplankton Dry Weight	18
Zooplankton Abundance and Biomass During the 1975 and 1976 Survey Cruises	22
Spring (April, May)	22
Summer (June, July, August)	27
Autumn (September, October)	29
Winter (December)	40
Principal Component Analysis with an Emphasis on the 1975 and 1976 Analyses	40
April	46
July	51
October	55
December	59
DISCUSSION AND SUMMARY	64

SECTION 2. EVALUATION OF THE EFFECTS OF PLANT OPERATION ON ZOO-PLANKTON POPULATIONS IN SOUTHEASTERN LAKE MICHIGAN DURING 1975 AND 1976

INTRODUCTION	69
HISTORY OF THE SURVEY PROGRAM	71
Stations	71
Nets	73
Replicate Samples	73
Subsampling Techniques	73
Taxonomic Identifications	73
METHODS	76
Analytical Design of the Survey Grid	76
Statistical Test Design	76
Zooplankton Taxa Tested	78
RESULTS	80
Temporal Abundance Patterns of Zooplankton in Zone 2 (1971-1976)	80
Statistical Comparisons of April Preoperational and Operational Abundances	84
Statistical Comparisons of July Preoperational and Operational Abundances	88
Statistical Comparisons of October Preoperational and Operational Abundances	89
DISCUSSION	96

SECTION 3. THE EFFECTS OF PLANT PASSAGE

INTRODUCTION	102
MATERIALS AND METHODS	102
Mortality Studies	102
Long-Term Incubation Studies	105
Heterogeneity Studies	105
RESULTS	106
Heterogeneity Studies	106
General Features of the 23-month Mortality Study	106
Statistical Analyses of the Mortality Data by Taxa and Incubation Time	112
DISCUSSION	121

SECTION 4. NUMBERS AND BIOMASS OF ZOOPLANKTON PASSING THROUGH THE POWER PLANT AND SETTLING TO THE SEDIMENTS

INTRODUCTION	125
MATERIALS AND METHODS	125
RESULTS	127
Seasonal Concentration of the Major Zooplankton Taxa in the Cooling Waters and in the Inshore Region	127

Epibenthic and Benthic Copepods and Cladocerans.	127
Numbers and Biomass of Zooplankton Passing through the Power Plant and the Estimated Maximum Losses	133
Depositional Area of Zooplankton Killed During Condenser Passage.	138
Depositional Rate of Dead Zooplankton.	141
DISCUSSION.	141
SECTION 5. DETAILED COMPARISONS OF ZOOPLANKTON POPULATIONS WITHIN AND ADJACENT TO THE THERMAL PLUME	
INTRODUCTION.	143
MATERIALS AND METHODS	143
RESULTS	145
DISCUSSION.	152
CONCLUDING REMARKS	157
REFERENCES	160
APPENDIX (Inside Back Cover)	

LIST OF FIGURES

Number	Page
1 Station locations for the major surveys and short surveys . . .	6
2 Surface-water temperatures and temperature-depth profiles along the DC-transect during cruises conducted in 1975 and 1976 . . .	11
3 Mean intake water temperatures ($^{\circ}$ C) over three day intervals from the water supply plant in St. Joseph, Michigan in March and April of the years 1972-1976	15
4 Secchi disc depths during cruises conducted in 1975 and 1976	19
5 Horizontal distributions (number/ m^3) of total zooplankton and major zooplankton taxa collected on 17 April 1975 and 14 April 1976	25
6 The standing stock of zooplankton (mg dry wt/ m^3) on 14 April 1976	27
7 The horizontal distribution (numbers/ m^3) of total zooplankton collected on 15 May 1975 and 12 May 1976	28
8 The standing stock of zooplankton (mg dry wt/ m^3) on 12 May 1976	29
9 The horizontal distribution of total zooplankton collected on 12 June 1975 and 17 June 1976	30
10 Standing stock of zooplankton (mg dry wt/ m^3) on 12 June 1975 and 17 June 1976.	31
11 Horizontal distribution (number/ m^3) of total zooplankton and major taxa collected on 17 July 1975 and 15 July 1976	32
12 The standing stock of zooplankton (mg dry wt/ m^3) on 17 July 1975 and 15 July 1976	35
13 The horizontal distribution of total zooplankton (number/ m^3) collected on 13 August 1975 and 11 August 1976	36
14 The standing stock of zooplankton (mg dry wt/ m^3) on 13 August 1975 and 11 August 1976	37

15	The horizontal distribution of total zooplankton (number/m ³) collected on 10 September 1975 and 24 September 1976	38
16	The standing stock of zooplankton (mg dry wt/m ³) on 10 September 1975 and 24 September 1976	39
17	Horizontal distribution (number/m ³) of total zooplankton and major taxa collected on 17 October 1975 and 14 October 1976 . .	41
18	The standing stock of zooplankton (mg dry wt/m ³) 17 October 1975 and 14 October 1976.	44
19	The horizontal distribution of total zooplankton (number/m ³) collected on 5 December 1975.	45
20	The standing stock of zooplankton (mg dry wt/m ³) on 5 December 1975.	45
21	Principal component ordination of survey stations sampled on 17 April 1975 and 14 April 1976.	48
22	Zooplankton abundance versus station depth on 17 April 1975 and 14 April 1976	49
23	Zooplankton composition versus station depth on 17 April 1975 and 14 April 1976	50
24	Principal component ordination of survey and beach stations sampled on 17 April 1975 and 14 April 1976.	52
25	Principal component ordination of the survey stations sampled on 17 July 1975 and 15 July 1976.	53
26	Zooplankton abundance versus station depth on 17 July 1975 and 15 July 1976.	54
27	Zooplankton composition versus station depth on 17 July 1975 and 15 July 1976.	56
28	Principal component ordination of the survey and beach stations sampled on 17 July 1975 and 15 July 1976	57
29	Principal component ordination of the survey stations sampled on 17 October 1975 and 14 October 1976.	58
30	Zooplankton abundance versus station depth on 17 October 1975 and 14 October 1976	60

31	Zooplankton composition versus station depth on 17 October 1975 and 14 October 1976.	61
32	Principal component ordination of the survey and beach stations sampled on 17 October 1975.	62
33	Principal component ordination of the survey stations sampled on 5 December 1975.	62
34	Zooplankton abundance and composition versus station depth on 5 December 1975	63
35	Thirty station major survey grid divided into the eight zones used in the pre-operational and operational comparisons	77
36	The monthly abundance of zooplankton in the inshore plume zone (zone 2) between 1970 and 1976.	81
37	Mean April densities of zooplankton by zone and year (1971-1976), and mean preoperational and operational zone densities	85
38	Mean July densities of zooplankton by zone and year (1971-1976), and mean preoperational and operational zone densities	91
39	Mean October densities of zooplankton by zone and year (1971-1976), and mean preoperational and operational zone densities	99
40	A schematic view of the condenser cooling-water system of the Cook Nuclear Plant.	103
41	Schematic view of the live zooplankton sampler (Zaggot Trap) and water flow through the trap and pump system	104
42	Intake and discharge water temperatures, 1975-1976.	108
43	Monthly mean mortalities (0-hour) for selected zooplankton taxa and the mean proportion of total zooplankton (%) accounted for by each taxa.	109
44	Monthly mean mortality of total zooplankton at each incubation time.	111
45	The survival of <u>Diaptomus</u> spp. in cultures of these organisms collected from the intake and discharge waters.	114

46	The survival of <u>Cyclops</u> spp. in cultures of these organisms collected from the intake and discharge waters.	115
47	The survival of nauplii and immature copepodites in intake and discharge cultures	116
48	Mean (over 23 months) immediate discharge mortality versus length.	119
49	Mean (over 23 months) immediate intake mortality versus length	120
50	Pump and net arrangement for zooplankton entrainment abundance samples	126
51	Graphical comparisons of zooplankton densities in the entrainment abundance samples and in the inshore zone	128
52	Variation in abundance of selected zooplankton taxa collected in entrainment abundance samples in 1976. Samples were collected weekly between July 23 and August 24.	132
53	Seasonal abundance of epibenthic zooplankton collected in the entrainment sampling program.	134
54	Estimates of the number of zooplankton entrained and maximum numbers lost during 1975-1976	136
55	Estimates of dry weight of entrained zooplankton and maximum losses during 1975-1976	137
56	The area over which 96% of the zooplankton killed during condenser passage settle to the sediments	139
57	Grid for the 25 September 1976 plume survey at 1-meter depth	144
58	The thermal plume at 1-meter depth on September 25, 1976. . . .	146
59	The distribution of selected taxa reaching maximum densities in the thermal plume at 1-meter on September 25, 1976.	148
60	The distribution of selected taxa reaching maximum densities in the thermal plume and in the ambient-temperature water at 1-meter on September 25, 1976	149
61	The distribution of <u>Bosmina longirostris</u> and <u>Polypheus pediculus</u> at 1-meter on September 25, 1976.	150

62	Ordination of 1-meter plume survey stations by principal components 1 and 2.	151
63	Plume survey grid with the zones derived from PC 1 and PC 2 . .	152
64	Regression equations and scatter plots of mean density versus water temperature for <u>Diaptomus</u> spp. C1-C5, <u>Bosmina longirostris</u> , and <u>Eubosmina coregoni</u>	153

LIST OF TABLES

Number	Page
1 Plume, discharge, and ambient-water temperatures, used to estimate the dilution of condenser-passed water and the proportion of condenser-passed water at DC-1.	17
2 Zooplankton dry weights derived by the filtration and selection methods for the field survey stations of 17 July 1975	21
3 Mean seasonal density of zooplankton taxa in four depth zones during 1975-1976.	23
4 The variance explained by principal components 1 and 2 in analyses of major survey samples.	46
5 Correlations between zooplankton taxa, station depth, Secchi disc depth, surface-water temperature and the first principal component	47
6 Summary of field survey sampling program.	72
7 Taxonomic resolution of zooplankton counts made between 1971 and 1976.	74
8 Results of Mann-Whitney U tests for April preoperative vs. operative period comparisons.	89
9 Results of Mann-Whitney U tests for July preoperative vs. operative period comparisons.	90
10 Results of Mann-Whitney U tests for October preoperative vs. operative period comparisons.	95
11 Percentage zooplankton mortality at three intake forebay sampling locations.	107
12 Percentage zooplankton mortality at three depths in the intake forebay.	107
13 Mean intake and discharge mortalities for 28 taxa	113
14 Zooplankton taxa for which discharge mortality was significantly higher than intake mortality	118
15 Sinking rates of selected zooplankton taxa.	140

16	Correlations between 17 zooplankton taxa and principal components 1 and 2, and temperature at 1 meter	154
----	-----------------------------------------------------------------------------------------------------------------	-----

The following Tables are in the Appendix on microfiche cards.

17	Mean abundances, standard errors, and percentages of zooplankton at each of 30 lake survey stations on April 17, 1975	1
18	Mean abundances, standard errors, and percentages of zooplankton at each of 7 zero line stations on April 17, 1975	10
19	Mean abundances, standard errors, and percentages of zooplankton at each of 14 lake survey stations on May 15, 1975	13
20	Mean abundances, standard errors, and percentages of zooplankton at each of 7 zero line stations on May 14, 1975	18
21	Mean abundances, standard errors, and percentages of zooplankton at each of the 14 lake survey stations on June 12, 1975	21
22	Mean abundances, standard errors, and percentages of zooplankton at each of the 7 zero line stations on June 10, 1975	26
23	Mean abundances, standard errors, and percentages of zooplankton at each of the 30 lake survey stations on July 17, 1975	29
24	Mean abundances, standard errors, and percentages of zooplankton at each of 7 zero line stations on July 16, 1975	38
25	Mean abundances, standard errors, and percentages of zooplankton at each of 30 lake survey stations on August 13, 1975	40
26	Mean abundances, standard errors, and percentages of zooplankton at each of 7 zero line stations on August 12, 1975	49
27	Mean abundances, standard errors, and percentages of zooplankton at each of 14 lake survey stations on September 10, 1975	52
28	Mean abundances, standard errors, and percentages of zooplankton at each of 7 zero line stations on September 10, 1975	57
29	Mean abundances, standard errors, and percentages of zooplankton at each of 27 lake survey stations on October 17, 1975	60
30	Mean abundances, standard errors, and percentages of zooplankton at each of 9 zero line stations on October 13, 1975	69

45	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on February 26, 1975	143
46	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on February 26, 1975	144
47	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on March 12, 1975	145
48	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on March 12, 1975	146
49	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on April 16, 1975	147
50	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on April 16, 1975	148
51	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on May 14, 1975	149
52	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on May 14, 1975	150
53	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on June 11, 1975	151
54	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on June 11, 1975	152
55	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on July 24, 1975	153

56	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on July 24, 1975	154
57	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on August 13, 1975	155
58	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on August 13, 1975	156
59	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on September 9, 1975	157
60	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on September 9, 1975	158
61	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on October 23, 1975	159
62	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on October 23, 1975	160
63	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on November 18, 1975	161
64	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on November 18, 1975	162
65	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on December 11, 1975	163
66	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on December 11, 1975	164

67	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on January 14, 1976	165
68	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on January 14, 1976	166
69	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on February 11, 1976	167
70	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on February 11, 1976	168
71	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on March 10, 1976	169
72	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on March 10, 1976	170
73	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on April 6, 1976	171
74	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on April 6, 1976	172
75	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on May 11, 1976	173
76	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on May 11, 1976	174
77	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on June 15, 1976	175

78	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on June 15, 1976	176
79	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on July 13, 1976	177
80	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on July 13, 1976	178
81	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on August 10, 1976	179
82	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on August 10, 1976	180
83	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on September 23, 1976	181
84	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on September 23, 1976	182
85	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on October 12, 1976	183
86	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on October 12, 1976	184
87	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on November 9, 1976	185
88	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on November 9, 1976	186

89	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the intake forebay on December 16, 1976	187
90	The mean and standard error of replicate determinations of the percent dead for each zooplankton taxa in the discharge forebay on December 16, 1976	188
91	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on January 30-31, 1975 . .	189
92	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on January 30-31, 1975 . .	190
93	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on February 26-27, 1975 .	191
94	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on February 26-27, 1975. .	192
95	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on March 12-13, 1975. . .	193
96	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on March 12-13, 1975 . . .	194
97	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on April 16-17, 1975. . .	195
98	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on April 16-17, 1975 . . .	196
99	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on May 14-15, 1975 . . .	197

100	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on May 14-15, 1975 . . .	198
101	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on June 11-12, 1975 . . .	199
102	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on June 11-12, 1975 . . .	200
103	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on July 24-25, 1975 . . .	201
104	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on July 24-25, 1975 . . .	202
105	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on August 13-14, 1975 . .	203
106	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on August 13-14, 1975. . .	204
107	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on September 9-10, 1975	205
108	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on September 9-10, 1975	206
109	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on October 23-24, 1975 . .	207
110	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on October 23-24, 1975	208

111	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on November 18-19, 1975	209
112	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on November 18-19, 1975	210
113	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on December 11-12, 1975	211
114	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on December 11-12, 1975	212
115	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on January 14-15, 1976	213
116	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on January 14-15, 1976	214
117	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on February 11-12, 1976	215
118	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on February 11-12, 1976	216
119	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on March 10-11, 1976.	217

120	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on March 10-11, 1976 . . .	218
121	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on April 6-7, 1976. . . .	219
122	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on April 6-7, 1976	220
123	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on May 11-12, 1976. . . .	221
124	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on May 11-12, 1976	222
125	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on June 15-16, 1976 . . .	223
126	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on June 15-16, 1976. . . .	224
127	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on July 13-14, 1976 . . .	225
128	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on July 13-14, 1976. . . .	226
129	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on August 10-11, 1976 . .	227
130	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on August 10-11, 1976. . .	228

131	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on September 23-24, 1976	229
132	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on September 23-24, 1976	230
133	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on October 12-13, 1976. . .	231
134	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on October 12-13, 1976 . .	232
135	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on November 9-10, 1976. .	233
136	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on November 9-10, 1976 . .	234
137	The mean concentrations, standard errors, and percent composition of zooplankton in the intake waters, and the mean number of zooplankton entering the plant per minute on December 16-17, 1976 .	235
138	The mean concentrations, standard errors, and percent composition of zooplankton in the discharge waters, and the mean number of zooplankton leaving the plant per minute on December 16-17, 1976. .	236

INTRODUCTION

New technological developments, increasing energy demands, and decreasing supplies of conventional fuels have led to the recent acceptance of nuclear power plants as economically feasible suppliers of energy. Although a number of small plants in the hundred megawatt capacity have been in operation since the 1950's, it was not until the late 1960's that both the number and size of nuclear power plants increased substantially (Sorge 1969). About this time, environmental pollution became a subject of immense public concern. As a result of these factors, nuclear and conventionally fueled plants became subject to more rigorous licensing requirements. One of these, section 316(a) of the Federal Water Pollution Control Act, requires that the thermal component of plant effluent be such that it will "assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on that body of water." This report addresses the effects of the operation of the Donald C. Cook Nuclear Power Plant on the zooplankton of southeastern Lake Michigan during 1975 and 1976.

The Donald C. Cook Plant is a two-unit plant which at full operational capacity will produce 2200 MWE. While the plant is only one of 45 nuclear and coal-fired plants on Lake Michigan, it is one of the largest. The Zion plant located north of Chicago is the only other similar-sized operational plant.

At full operational capacity, the Donald C. Cook Plant will utilize approximately 6,300 m³ of lake water each minute for its once-through cooling system. This rate is equivalent to the mean annual flow rates of any one of the four largest rivers (Fox, St. Joseph, Grand, Menominee) discharging into Lake Michigan (U.S. Department of the Interior 1968). Zooplankton passing through the power plant are exposed to temperature increases of up to 12 C° above ambient for a period of approximately three minutes. In the thermal plume, exposure times to temperatures 2.8 C° (5 F°) above ambient are in the order of 20 minutes while exposures to temperatures 1.7 C° (3 F°) above ambient are in the order of 142 minutes (United States Atomic Energy Commission 1973).

A large body of literature is accumulating which documents the effects of thermal discharges on zooplankton communities in a number of fresh, brackish, and marine water habitats. The subject is exceedingly complex and factors such as zooplankton composition, discharge water temperature, ΔT , season, plant design, morphometry of the receiving water body, and survey grid design are all crucial in determining whether or not changes in zooplankton populations due to plant operation can be detected. In general, power plants operating at lethal temperatures and discharging comparatively large volumes of water into small receiving water bodies do have detectable effects on zooplankton populations. Conversely, power plants operating at sublethal temperatures and discharging comparatively small volumes of water

into large receiving water bodies do not have any immediately detectable effect on zooplankton populations. The Donald C. Cook plant is in this second category.

The upper lethal limit for most aquatic organisms has not been determined. Drost-Hansen (1969) suggested that it is probably in the mid-30's $^{\circ}\text{C}$ range. Laboratory studies using Cyclops spp. and Diaptomus spp. (Industrial Bio-Test Laboratories 1974a) and field studies (Reeve 1970; Davies and Jensen 1974) tend to support this hypothesis. Some zooplankton which can live and reproduce at temperatures in the lower 30's $^{\circ}\text{C}$ experience high mortalities after a few minutes exposure to temperatures an additional 1 or 2 $^{\circ}\text{C}$ higher (Brown and Crozier 1927-28). Upper lethal temperatures depend upon a number of factors including acclimation temperature and ΔT .

Zooplankton mortalities during condenser passage are minimized when discharge water temperatures do not exceed 35 $^{\circ}\text{C}$ and the ΔT 15 to 20 $^{\circ}\text{C}$. Plume entrainment mortalities are minimized when heated discharge waters are rapidly cooled. Mortalities may be high in long, narrow receiving water bodies such as discharge canals and river channels. Subsurface discharge jets (as at the Donald C. Cook plant) increase the rate at which discharge water is cooled and can substantially reduce the effect of heated effluents on the receiving water body (Eiler and Delfino 1974). In grossly polluted waters or in areas where significant portions of the receiving water body are heated, the construction of cooling towers may be the only viable alternative (Ross and Whitehouse 1973).

Exposure to temperatures less than 35 $^{\circ}\text{C}$ while generally non-lethal, affects a number of physiological processes including growth, reproduction, feeding, and longevity (Brown 1926-27, 1929; Brown and Crozier 1927-28; MacArthur and Baillie 1929a, b; Pratt 1943; Green 1956; Hall 1964; Comita 1968; Naylor 1965; Heinle 1969). If exposure times are sufficiently long, changes in zooplankton physiology may result in detectable alterations such as changes in zooplankton community structure and biomass (Zhitjenjowa and Nikanorow 1972; McMahon and Docherty 1975; Markowski 1962; Whitehouse 1971), and changes in production rates and ecological efficiencies (Patalas 1970). Such alterations have been detected for temperatures in the mid-20's $^{\circ}\text{C}$ and have been limited to small water bodies (lagoons, harbors, small lakes) where the cooling rate of heated water and the transport rate of zooplankton away from the plant have been low. Power plants operating on large bodies of water such as Lake Michigan have generally had no detectable effect on zooplankton communities.

This report presents the results of studies conducted in 1975 and 1976 evaluating the effects of the operation of Unit 1 of the Donald C. Cook Nuclear Power Plant on the zooplankton of southeastern Lake Michigan. Although our studies began in 1969, it was not until February 1975 that the first unit of the plant was operational. Consequently this is our first operational report.

The main body of the report consists of five sections. The first section describes zooplankton distributions over the survey area in 1975 and 1976. In the following section, we compare seasonal patterns of zooplankton abundance in the thermal plume region before and during plant operation to determine if plant operation has resulted in the advancement of seasonal cycles. In this second section, we also make statistical comparisons of zooplankton abundances in each of eight zones of the survey grid between preoperational and operational periods.

The third and fourth sections of the report focus on the direct effects of condenser passage. In section three, we describe the mortality levels of zooplankton that passed through the power plant, and relate these mortalities to water temperature, zooplankton size, and plant pumping rate. In the fourth section, the number and biomass of zooplankton passing through the cooling system and the numbers and biomass killed are estimated. Using these data, we estimate the area over which these dead zooplankton settled from the water column to the sediments. The fifth section presents the results of an intensive study examining zooplankton distributions within and adjacent to the thermal plume and shows the magnitude and areal extent of changes which can occur. A concluding section interrelates the results of the zooplankton studies, discusses some of the limitations in our monitoring program, and suggests areas which require further investigation.

SECTION 1

THE SEASONAL AND SPATIAL DISTRIBUTIONS OF ZOOPLANKTON DURING THE 1975 AND 1976 SURVEY CRUISES

INTRODUCTION

Zooplankton are weakly motile animals carried by water currents from one area to another. In Lake Michigan zooplankton collected in our 158 μ aperture nets generally range in size from 0.2 to 2.0 mm. Crustaceans, and in particular copepods and cladocerans, dominate these collections.

Zooplankton abundance varies seasonally, ranging from less than 1,000/m³ to more than 200,000/m³. Copepods are the numerically dominant forms during the winter and spring, and cladocerans are the numerically dominant forms during the summer and autumn. Zooplankton also exhibit spatial variations in abundance in response to factors such as phytoplankton composition, the presence of predators, and water depth. Events such as upwellings can alter the zooplankton concentration in an area over a matter of hours.

Human activities have produced both spatial and temporal alterations in zooplankton populations. Chemical pollutants (nutrients, heavy metals, etc.) have produced disturbed populations in areas such as Green Bay where zooplankton populations are distinct from populations in other nearshore areas of the lake (Gannon 1972). Over the past few decades, the chemistry of Lake Michigan has undergone change with many elements increasing in concentration; associated with these changes have been changes in the biota (Beeton 1969). For example, the brackish-water copepod Eurytemora affinis invaded Lake Erie by the early 1960's (Engel 1962) and is now common in the nearshore summer plankton of Lake Michigan.

There is now concern that increased power plant activity on Lake Michigan with its useage of substantial volumes of lake water may result in temporal and spatial alterations in lake biota, including zooplankton. Our lake sampling program which includes a large survey grid (Fig. 1) and spans multiple years of preoperational and operational monitoring is designed to detect power plant related changes in zooplankton populations over a substantial area (250 km²) of the lake.

Preoperational studies have determined the major limnological features of this area of the lake. Water tends to flow in a northerly direction parallel to shore, and there is some exchange of water between the inshore and offshore regions. The Michigan City-Benton Harbor Eddy lies in the outer reaches of the survey area during part of the spring, summer, and autumn (Ayers et al. 1958; Ayers et al. 1967). Nutrient-enriched water enters the survey grid from the north (St. Joseph River) and from the south. Enriched

water also enters the survey grid from the Bridgeman sewage plant (3 km south of the plant site) and from streams south of Warren Dunes State Park. Differences in water flow and chemistry have resulted in both alongshore and inshore-offshore differences in sediment composition (Rossmann 1975).

Macrobenthic populations vary in abundance and composition with distance from shore and, to a lesser extent, alongshore (Mozley 1973, 1974; Johnston 1973). Similar differences occur in the fish populations inhabiting southeastern Lake Michigan (Wells 1968; Jude et al. 1975).

Plankton exhibit less consistent alongshore variations in abundance than do the benthos and probably the fish. This is probably because plankton are carried through the survey grid by currents which vary in speed and direction under various meteorological and lake conditions. Phytoplankton populations (collected from 1 m) exhibit only slight inshore-offshore differences in abundance (Ayers 1975) while zooplankton (collected from the entire water column) exhibit pronounced inshore-offshore differences in abundance in most months (Roth 1973; Stewart 1974; Evans 1975). We examined the spatial variations in zooplankton abundances in 1974 and identified two or three depth-related groupings of stations (Evans and Hawkins 1975).

This section describes zooplankton distributions in 1975 and 1976 over the survey grid. It also presents the results of additional analyses of zooplankton populations in this area of the lake. The thermal characteristics of the water column, the location of the thermal plume, and Secchi disc depths are presented for each cruise.

MATERIALS AND METHODS

The Survey Grid

The survey grid (Fig. 1) extends 11 km north and south of the plant site and 11 km offshore. The closest power plant south of the Donald C. Cook Nuclear Power plant is the Michigan City Generating Station (34 km), a 203 MWe plant which utilizes both a cooling tower and once-through cooling. To the north (55 km) is the Palisades Nuclear Power Plant, a 811 MWe facility (Krezoski 1969) which now employs cooling towers.

Major surveys (Fig. 1a) and short surveys (Fig. 1b) are conducted monthly from April through November. Major surveys presently consisting of 30 stations provide detailed information on zooplankton community structure during the spring (April), summer (July), and autumn (October). Short surveys presently consisting of 14 stations provide information on zooplankton population dynamics during the intervening months.

The original (1970) survey grid consisted of 46 stations. The current

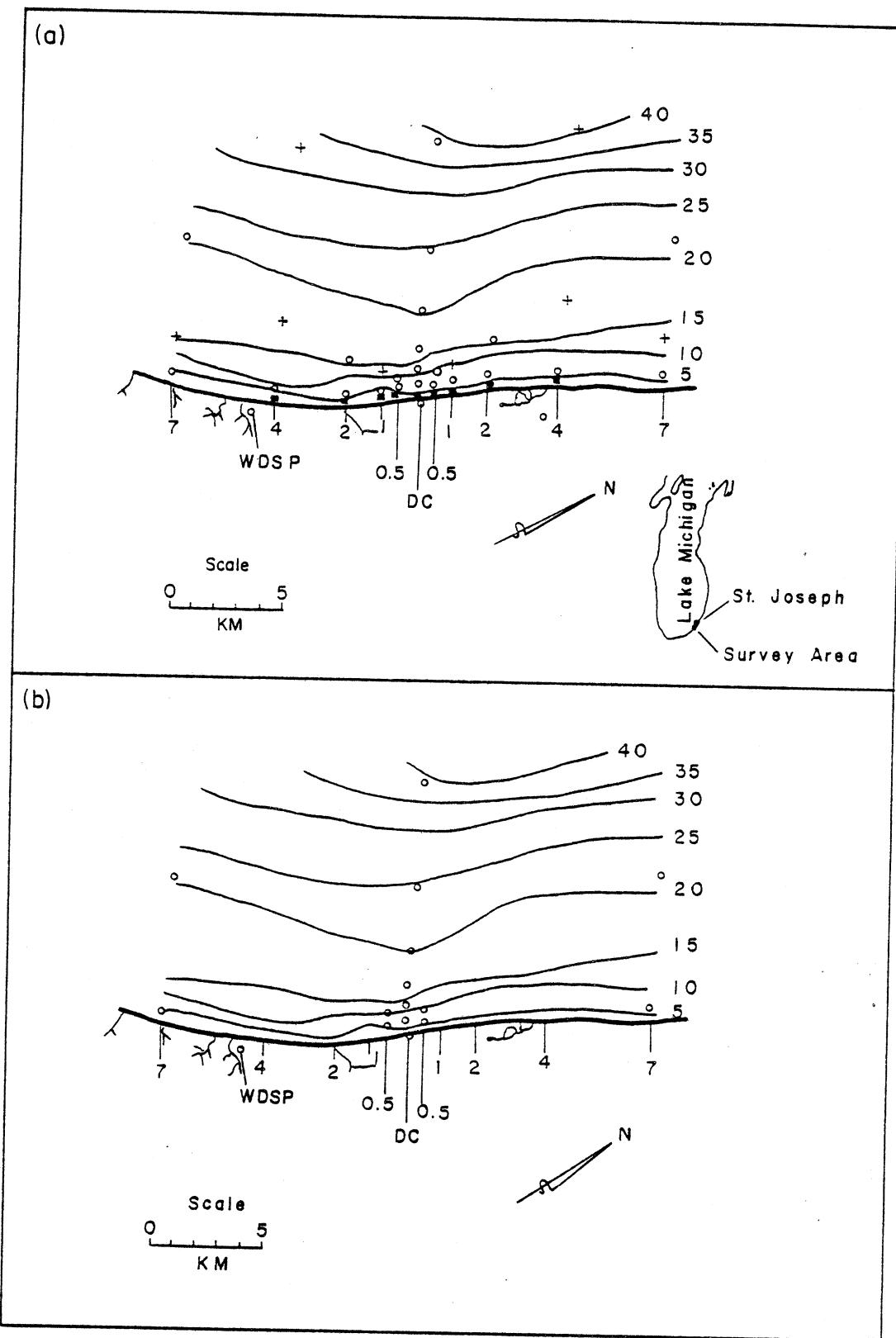


FIG. 1. Station locations for the major surveys (a) and short surveys (b). Beach region stations (■) are included on the major survey grid. Depth contours are in meters. Other symbols: \circ indicates a station where all species were enumerated; $+$ indicates a station where only genera were enumerated. WDSP indicates Warren Dunes State Park.

monitoring program consists of 30 or 14 station subsets of the original grid. A two-part numbering system was used to name each station. The first part, DC, NDC x, or SDC x refers to the location of a transect relative to the plant site. The DC transect extends directly offshore from the plant, and the NDC x and SDC x transects are respectively x miles north or south of the plant site. The second part of each station name designates the station number in a transect series. For example, DC-1 is the first station along the DC transect and DC-6 the sixth. DC-6 is as far offshore as NDC 4-4, the fourth station in the NDC 4 transect.

For the major survey cruise grid (Fig. 1a) the six stations along the DC transect have been retained, stations 1 and 2 of the original three of NDC 1 and SDC 1 transects, stations 1 and 3 of the original three of the NDC 2 and SDC 2 transects; stations 1, 3, and 4 of the original four of the NDC 4 and SDC 4 transects; and stations 1, 3, and 5 of the original five of the NDC 7 and SDC 7 transects have also been retained.

Station depth ranges from 4 m to over 40 m and increases with distance from shore (Fig. 1). On occasion, additional stations (Fig. 1a) were sampled from a Boston Whaler in one or two meters of water (the beach region). These stations are designated as DC-0, NDC 1-0, SDC 2-0, etc. and are equivalent to the phytoplankton "zero line" of stations.

The three intake pipes utilized by the power plant are located approximately 690 m offshore (between stations DC-1 and DC-2) in 7.3 m of water. The intakes form the apexes of a 75 m equilateral triangle. Two discharge pipes will be used to return heated water to the lake during two-unit operation. In 1975 and 1976, only the north pipe was utilized. The two pipes are located approximately 379 m offshore (station DC-1) in 5.5 m of water and are 100 m apart.

Physical Measurements

Surface-water temperatures were measured at each station with a thermometer immersed in a bucket of freshly collected water and/or with a YSI thermistor probe suspended a few centimeters below the water surface. Temperature-depth profiles were measured with an electronic bathythermograph and a chart recorder. Temperature could be read to $\pm 0.5^{\circ}\text{C}$ and depth to ± 0.25 m. At each station, both ascending and descending traces were recorded. Temperature-depth profiles were not always obtained due to equipment malfunctions.

Secchi disc depths were measured using an 8-inch (20.3 cm) diameter white disc. Data are missing from stations sampled after sunset; this generally occurred only during the April cruises.

Zooplankton Sampling Methods

Methods used to collect zooplankton in 1975 and 1976 were the same as in 1973 (Stewart 1974) and 1974 (Evans 1975). Major surveys were conducted in August 1975 and May 1976 (rather than short surveys) because the power plant was not discharging heated water during the regularly scheduled major survey cruises (July, April). Poor weather and rough lake conditions prevented completion of the October major survey cruises and forced cancellations of the November cruises. A December 1975 short survey was made in order to provide information on zooplankton population dynamics during the winter. Samples were also collected at the phytoplankton zero-line stations (Fig. 1a) located in the beach region in April, June, and July of both years and in May, August, September, and October 1975. These samples were collected to provide more information on zooplankton distribution patterns in the shallow areas of the survey grid.

Zooplankton were collected at each station with a 50-cm diameter net (158 μ aperture). A calibrated flowmeter mounted in the mouth of the net measured the volume of water filtered during each vertical haul. Three hauls were made at each station from as close to the bottom as possible (approximately 1 m) to the surface. The flowmeter was read, the outside of the net was washed down with water from a hose, and the contents of the plankton bucket were transferred to a labelled jar and preserved with Koechie's fluid, a sugar-formalin solution (2.3 kg sugar dissolved in 2 liters of concentrated formalin and 8 liters of water).

Counting Techniques

In the laboratory, zooplankton in the first two replicate samples were counted. The third sample was retained as a spare sample to be counted if there was poor agreement between the counts in the first two replicates; this did not occur in 1975 or 1976. Each sample was subdivided as many times as necessary in a Folsom plankton splitter to give two subsamples of 350 to 500 organisms each. A third subsample of 700 to 1,000 organisms was examined for the rare taxa (less than 40 animals and 10% of the two subsamples). Cladocerans and adult copepods were identified to species level at all short survey stations and at 22 of the 30 major survey stations; identifications were to genus level at the remaining eight stations (Fig. 1). Adult copepods were distinguished by sex at all stations. Immature copepodites were identified to genus while nauplii were combined as a group. Taxonomic keys referred to included Pennak (1963), Deevey and Deevey (1971), and Wilson, Tressler, and Yeatman in Edmondson (1959). Zooplankton were enumerated in a circular counting dish using a microscope at a magnification of 20 to 140X.

Dry Weight Determinations

A new method for determining zooplankton biomass was used in 1975 and

1976. Prior to 1975, plankton samples were filtered onto a preweighed, oven-dried filter, heated at 100°C for several hours, and weighed. However, high concentrations of phytoplankton and detritus in samples collected in the nearshore area, particularly in the spring and autumn, precluded reliable biomass estimates from being obtained at more than 50% of the stations. In order to circumvent this problem, an alternate method was developed. This involved determining the mean dry weight of individual zooplankton taxa and then calculating the biomass of total zooplankton in the water column based on the concentrations and weights of the various taxa.

Each month, 3 to 30 preserved animals from the numerically dominant taxa were washed in distilled water, placed in preweighed aluminum boats (0.5 cm diameter), dessicated for at least 48 hours over silica gel absorbent at room temperature, and weighed on a Cahn Electrobalance. Lovegrove (1966) recommended dessication for small samples to avoid weight loss due to excessive drying and volatilization of oils which may occur with oven drying at temperatures as high as 100°C.

Biomasses were determined from samples collected at DC-1 and DC-6 for most taxa. Some taxa were rare at one of the two stations, so estimates were made at only one station. A few taxa, generally less than 5% of the total zooplankton, were so rare that their dry weights were not determined. We did not observe any consistent difference in mean dry weight of the various taxa between the two stations and so averaged the results to obtain a mean biomass estimate for each taxon over the survey grid during a particular cruise. An estimate of zooplankton dry weight (mg/m^3) at each station was calculated by summing the product of the mean biomass ($\mu\text{g}/\text{individual}$) and the density ($\text{numbers}/\text{m}^3$) for each taxon. The mean dry weight per individual at each station was calculated by dividing the total sample biomass by the number of individuals.

Principal Component Analyses

In the 1974 preoperational report, we used principal component ordination to identify groups of stations with similar zooplankton abundances and compositions. Three groups were identified which corresponded with water depth, i.e., an inshore region extending between the 5 and 10-m depth contours, a middle region extending out to the 15 or 20-m depth contours, and an offshore region extending at least as far as the 45-m depth contour. These analyses utilized April, July, and October cruise data collected only in 1974 (Evans and Hawkins 1975).

In order to determine if the results of the 1974 analyses were representative of the preoperational period, we repeated the ordinations using 1972 and 1973 data. In order to compare the three preoperational April data sets, we used the same zooplankton taxa in each analysis. Similarly, we used the same taxa for the July and the October analyses. We also performed similar ordinations using the April, July, and October 1975 and 1976 major cruise data. Beach region stations were included in additional 1975 and 1976

analyses to determine whether or not stations in waters shallower than 4 m were a continuum of the inshore region or were a distinct region of the lake. A final operational analysis utilized the December 1975 short survey cruise data. In this section, we report the results of the 1975 and 1976 analyses; similar results were obtained with the 1972, 1973, and 1974 data sets except where noted.

The analyses were performed by utilizing the variance-covariance matrix of the log-transformed (numbers/m³ + 1) taxa data. Generally if a taxon was used in an analysis it accounted for at least 1% of the zooplankton at several stations during each multi-year month (April, July, or October) comparison. Seven taxa were used for the April analyses, 12 for the July analyses, and 13 for the October analyses. Nine taxa were used in the December 1975 analysis. Correlations between the principal components and the log-transformed original variates were performed to assist with the interpretation of the principal components. The analyses were performed by using the PRINCOM program incorporated into the Michigan Interactive Data Analysis System (MIDAS) on the AMDAHL 470V/6 computer at the University of Michigan.

RESULTS

Water Temperatures

Surface-water temperatures were slightly higher (1-3 C°) on cruise dates in April, May, and June 1976 than in 1975, and temperatures were 1 to 3 C° lower in July, August, and September 1976 than in 1975. Water temperatures were slightly higher (1 C°) in October 1976 than in the preceding year (Fig. 2). Thermal stratification developed in the water column in the spring and persisted through the summer. The water column was well mixed at most stations by the October cruises. The loss of thermal stratification appeared to have occurred later in 1975 than in 1976.

While some of the differences in water temperature between 1975 and 1976 may have been associated with cruise timing, most were probably associated with weather variability. Spring of 1976 was characterized by unseasonably warm temperatures and this had an obvious effect on lake water temperatures. Water temperatures during the April 1976 cruise and during the weeks prior to the cruise were up to 6 C° higher than during previous years (1972 to 1975).

Information on water temperatures during the weeks preceding the five (1972 to 1976) April cruises was obtained from the St. Joseph filtration plant located 16 km north of the Cook plant. The filtration plant withdraws water from the 6 m depth contour. Since the water column was probably isothermal from October to early May in this shallow region of the lake, these filtration plant data should provide a good indication of water temperatures in the nearshore area of the survey grid at comparable periods of time. Water temperatures (Fig. 3) clearly were higher in March and April

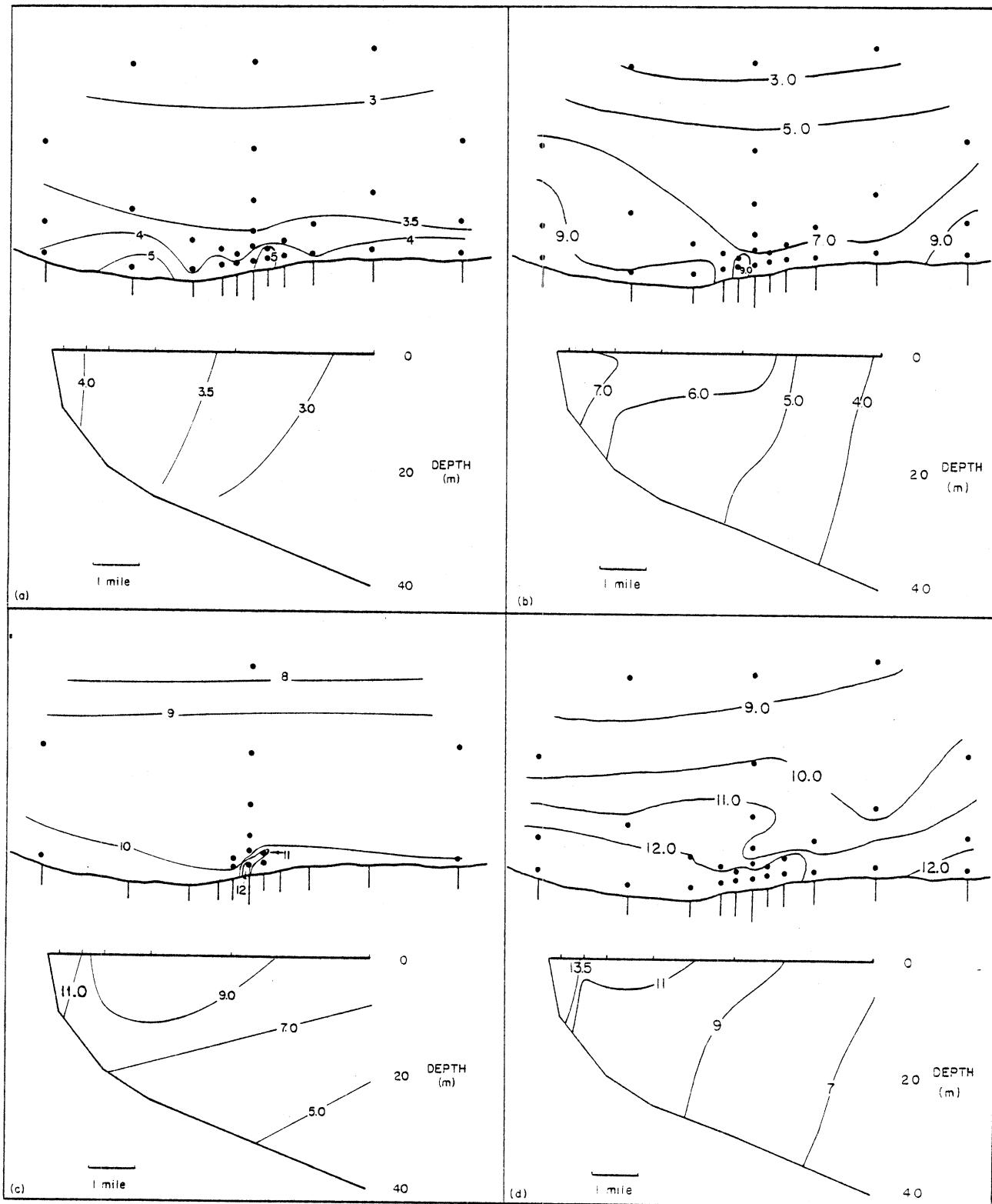


FIG. 2. Surface water temperature and temperature-depth profiles along the DC transect in a) 17 April 1975, b) 14 April 1976, c) 15 May 1975, d) 12 May 1976.

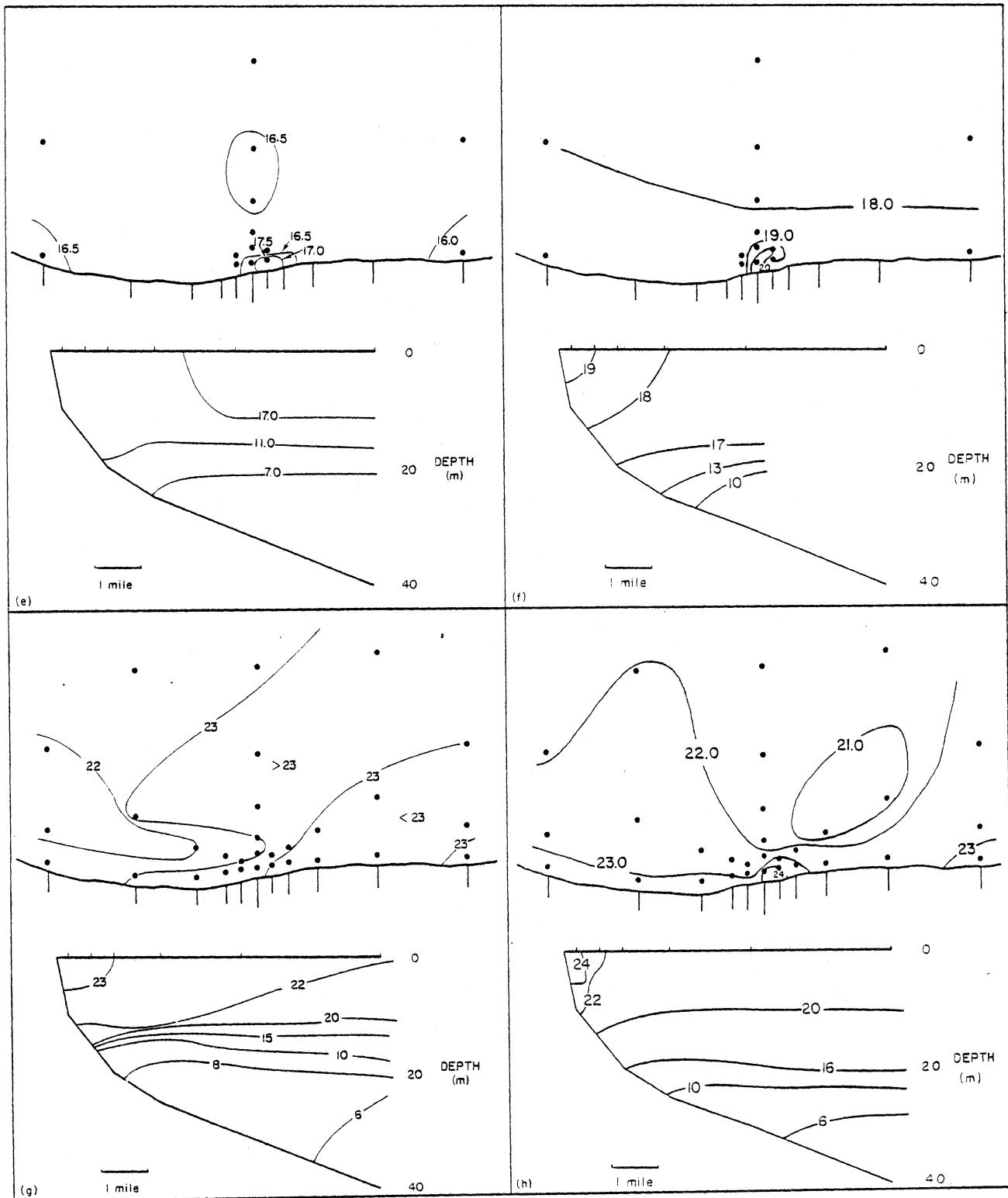


FIG. 2 continued. e) 12 June 1975, f) 17 June 1976, g) 17 July 1975, h) 15 July 1976.

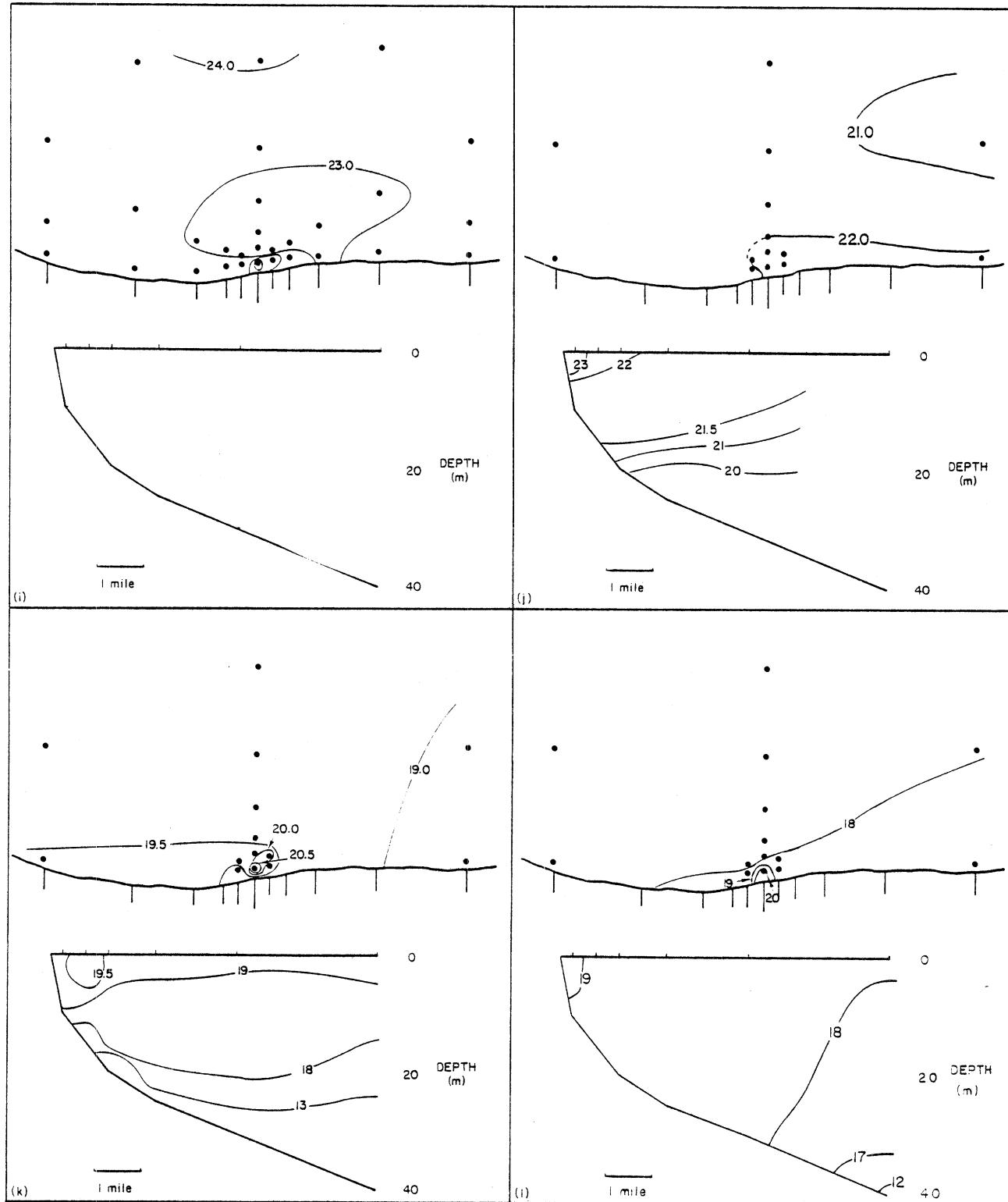


FIG. 2 continued. i) 13 August 1975, j) 11 August 1976, k) 10 September 1975, l) 24 September 1976.

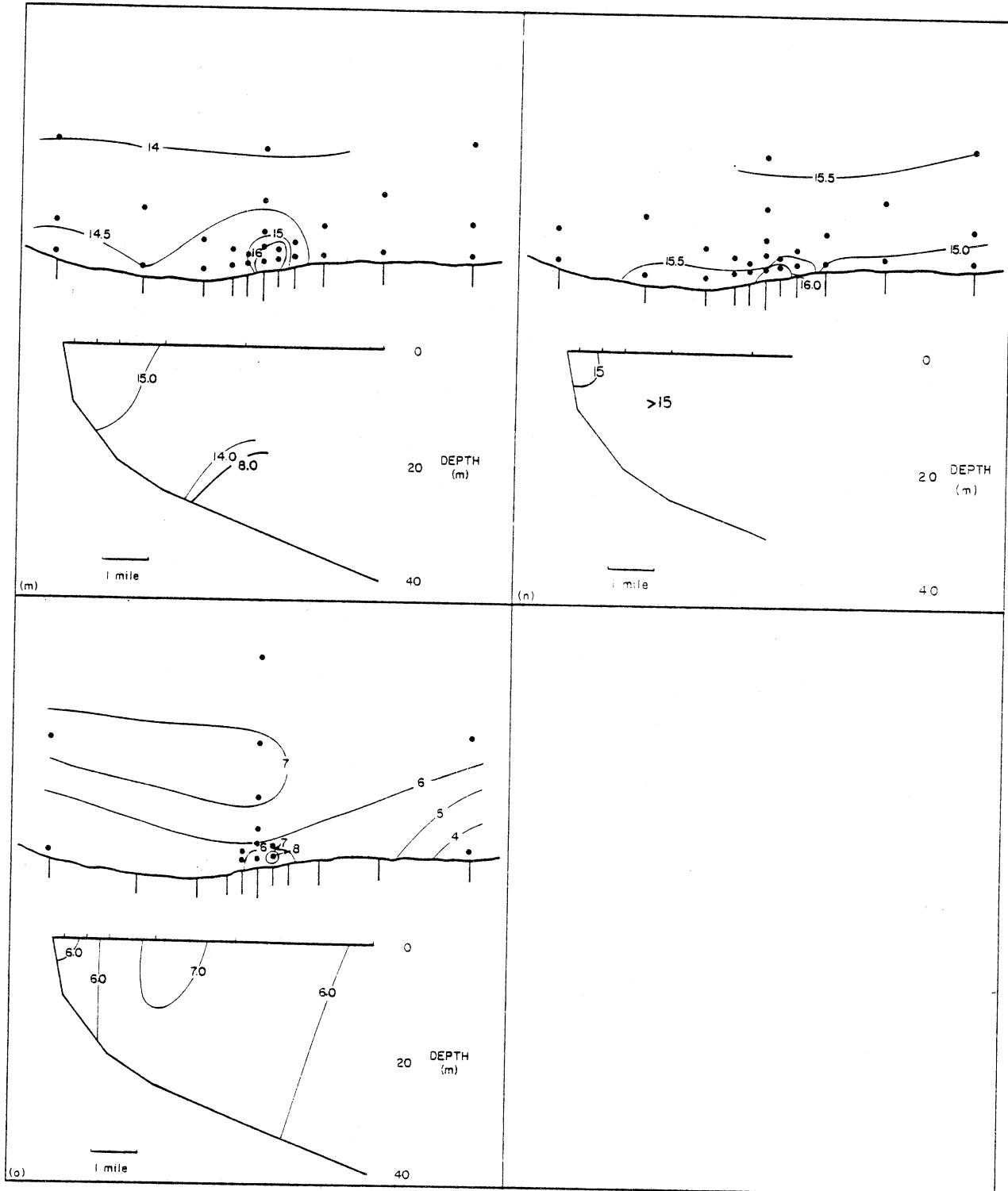


FIG. 2 continued. m) 17 October 1975, n) 14 October 1976, o) 5 December 1975.

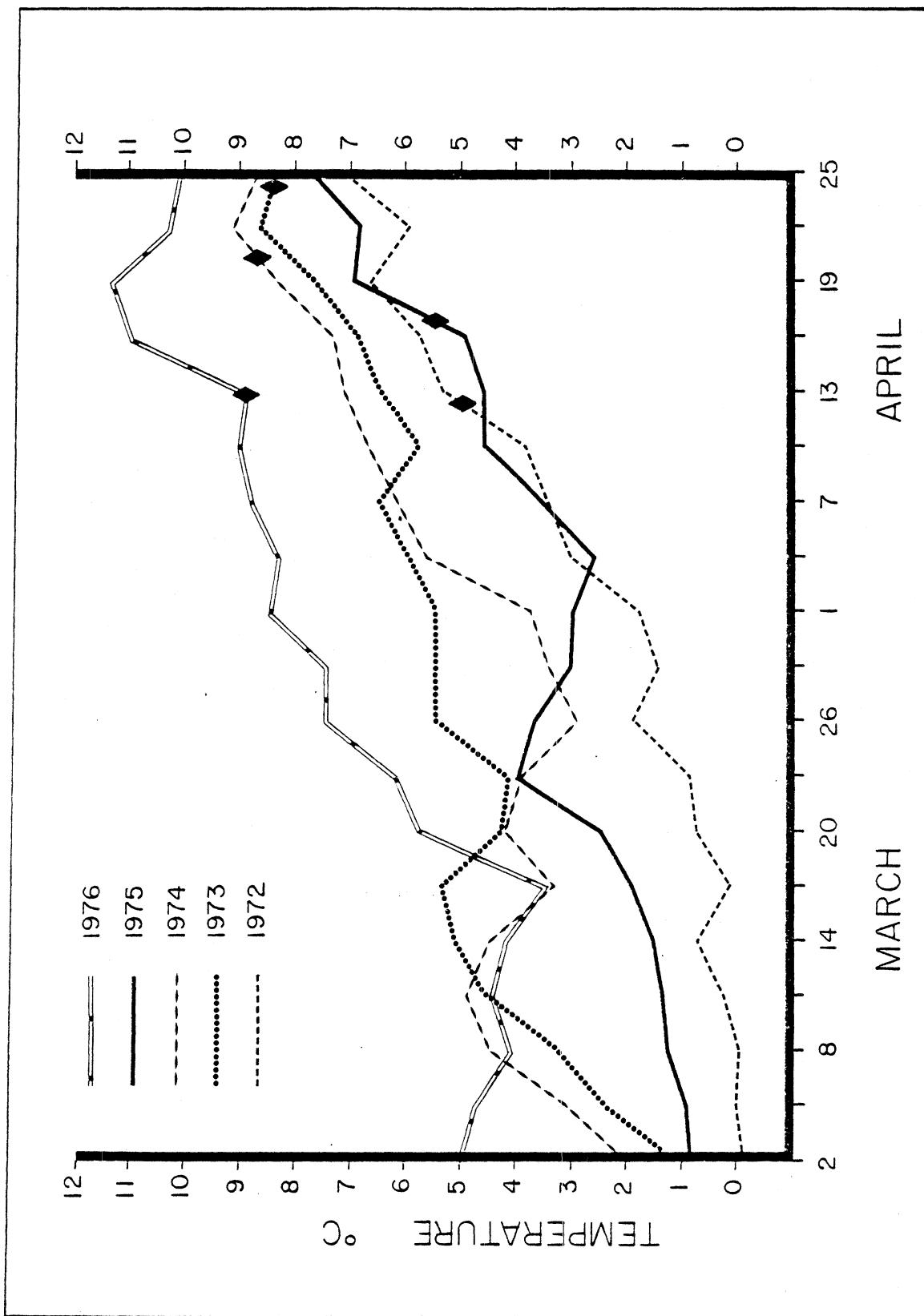


FIG. 3. Mean intake water temperatures ($^{\circ}\text{C}$) over three day intervals from the water supply plant in St. Joseph, Michigan in March and April of the years 1972-1976. (A \blacklozenge indicates the date on which the survey grid was sampled in April of each year.)

1976 than in the preceding years. April 1972 and 1975 were comparatively cold months while 1973 and 1974 were relatively warm. Differences in water temperatures between years, while slight, may have profound effects on the biological community.

The thermal plume produced by the Cook plant was generally detectable ($\Delta T 0.5 C^\circ$) only within one or two kilometers of the plant site (Fig. 2). The apparent direction of plume flow contrasts with the results of the detailed plume mapping studies conducted by power plant personnel who determined that the direction of plume ($\Delta T 1.2 C^\circ$) flow was generally to the northwest (Indiana and Michigan Power Company 1976). Differences in the results of the two studies may be associated with differences in the number of stations sampled in the thermal plume region and with the ΔT considered. The power plant investigators conducted underway plume mapping studies obtaining thousands of temperature measurements in the area where the plume was undergoing its initial dilution. In contrast, only three or four of our stations were in the thermal plume and, at the $\Delta T 0.5 C^\circ$ isotherm, we may have been detecting eddies rather than the main body of the plume.

Calculations were performed to estimate the dilution of condenser-passed water at DC-1, located within meters of the discharge jets. The equation used was:

$$X = \frac{P - A}{D - A}$$

where X = proportion of condenser-passed water

P = mean temperature of the water column at DC-1

D = discharge water temperature (measured by plant personnel from inside plant)

A = mean temperature of ambient water near the discharge jets.
The temperature at SDC .5-1 generally was used.

Condenser-passed water was strongly diluted (Table 1) over the discharge jets and composed less than 30% of the water at the jets in most months. In each month, there was no apparent relationship between the amount of mixing, and wind speed and direction. Most of the variation was probably associated with slight differences in ship location over the discharge jets. In the highly turbulent area over the discharge jets, the ship may move several tens of meters in a matter of minutes and different fractions of water may be sampled in the same time period. The results of these calculations do indicate that condenser-passed water is rapidly diluted by the discharge jets over a very small area of the survey grid.

TABLE 1. Plume, discharge, and ambient-water temperatures used to estimate the dilution of condenser-passed water and the proportion of condenser-passed water (X) at DC-1.

	Plume water at DC-1 (°C)	Discharge water (°C)	Ambient water (°C)	% of condenser- passed water at DC-1
	P	D	A	X
Apr 75	4.2	13.8	4.5	nd
76	- - - - -	no heated water	- - - - -	
May 75	12.2	17.4	9.4	35.0
76	14.7	22.9	11.0	31.1
Jun 75	18.6	23.6	15.8	35.9
76	20.3	30.9	18.7	13.1
Jul 75	- - - - -	no heated water	- - - - -	
76	24.8	34.0	22.7	18.6
Aug 75	24.8	30.7	22.8	25.3
76	22.8	33.8	21.8	8.3
Sep 75	19.4	26.6	19.4	nd
76	20.4	30.4	17.9	20.0
Oct 75	17.5	23.3	15.1	29.2
76	16.4	27.8	15.6	6.6
Dec 75	5.7	14.8	5.4	3.2

nd = not detectable

Secchi Disc Depths

Secchi disc depths approximately represent the transparency of surface water. Reduction in transparency may be of biological (phytoplankton) or physiochemical origin. Secchi disc depths over the survey grid followed the preoperational pattern with depths increasing with distance offshore (Fig. 4). Values were about the same in the region of the thermal plume as at comparable depths further away, which suggests that phytoplankton standing stocks were similar within and adjacent to the plume.

Secchi disc depths were low in April, high in May, June and July, and decreased in August, remaining low for the remainder of the year. Secchi disc depths were lower in 1976 (with the exception of April and August) than in 1975. The lower transparencies in September and October 1976 may have been associated with the earlier loss of thermal stratification than in 1975. Vertical mixing of the water column which occurred at this time probably released hypolimnetic nutrients to the surface stimulating an increase in primary production.

Comparison of Old and New Methods for Determining Zooplankton Dry Weights

Zooplankton dry weights derived from the filtration method (Table 2) were generally higher than those obtained with the selection method. Since the true values for these weights are not known, it is somewhat difficult to judge which method produced the best absolute estimates of biomass. However, the selection method produced weights which were more consistent with the field survey abundances and certain trends appeared in the results using the selection method which did not appear in the filtration method results. For example, zooplankton concentrations increased with distance from shore out to the 25-m depth contour and then decreased further offshore. Biomass estimates as determined by the selection method mirrored this trend with weights increasing out to DC-4, SDC 7-5, and NDC 7-5, and then decreasing with further distance from shore (NDC 4-4, SDC 4-4, DC-5, DC-6). The filtration method did not show this pattern and weights (mg/m^3) were greater at DC-1 and SDC 7-1 than at some stations further from shore despite the fact that the absolute numbers of zooplankton were smaller. Since the zooplankton at these stations were not dominated by large forms, this is clearly an error due to debris and phytoplankton contributing significant fractions of material to the dry weight estimates. In addition, the selection method produced consistent estimates of mean zooplankton dry weight with values ranging from 1.0 to 2.0 $\mu\text{g/individual}$ while the filtration method produced less consistent values ranging from 0.3 to 8.5 $\mu\text{g/individual}$. The selection method is superior to the filtration method because it avoids errors which arise when plankton samples are heavily "contaminated" with phytoplankton and debris as is common in the nearshore area.

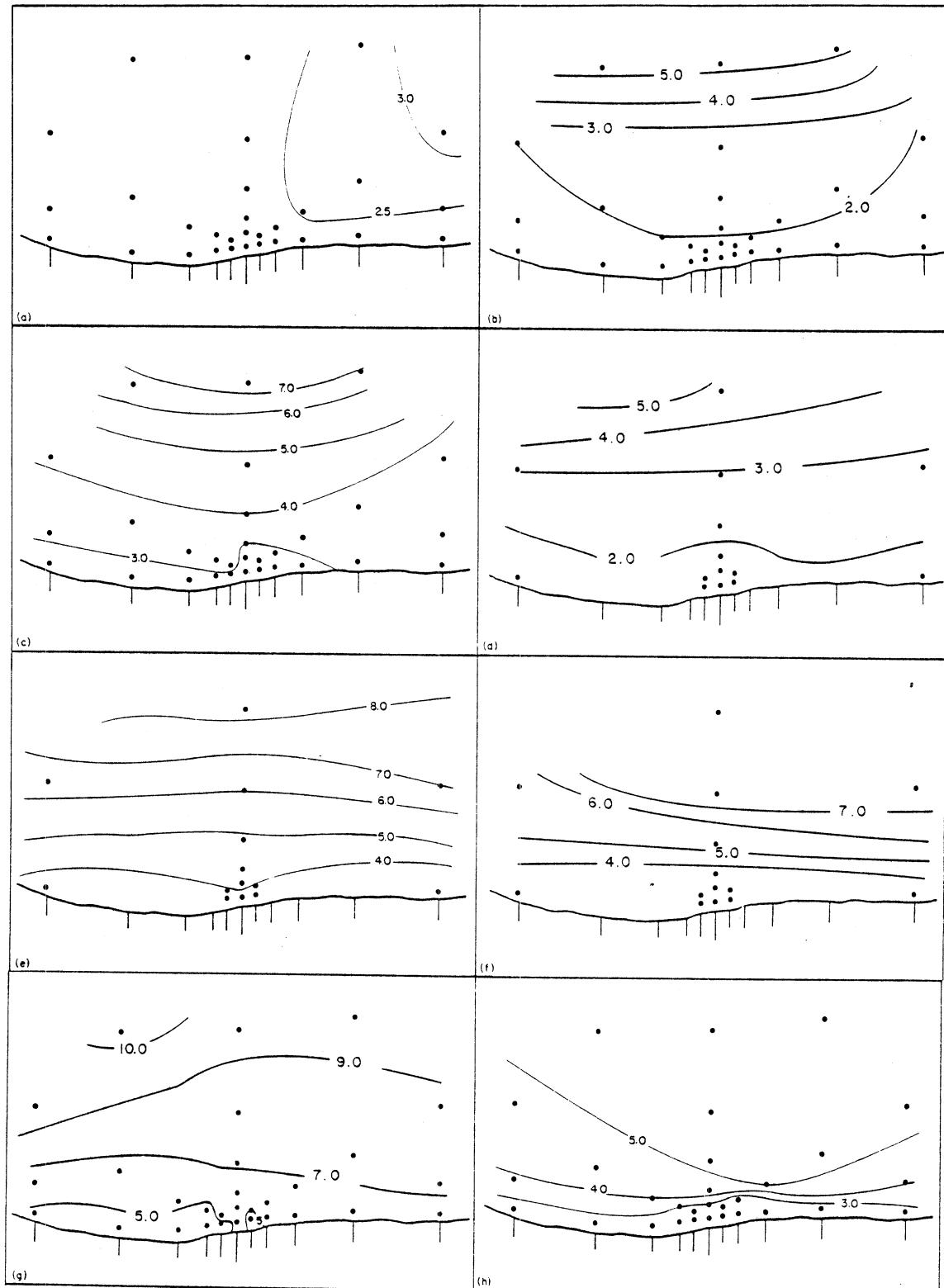


FIG. 4. Secchi disc depths in meters for in a) 17 April 1975, b) 14 April 1976, c) 15 May 1975, d) 12 May 1976, e) 12 June 1975, f) 17 June 1976, g) 17 July 1975, h) 15 July 1976.

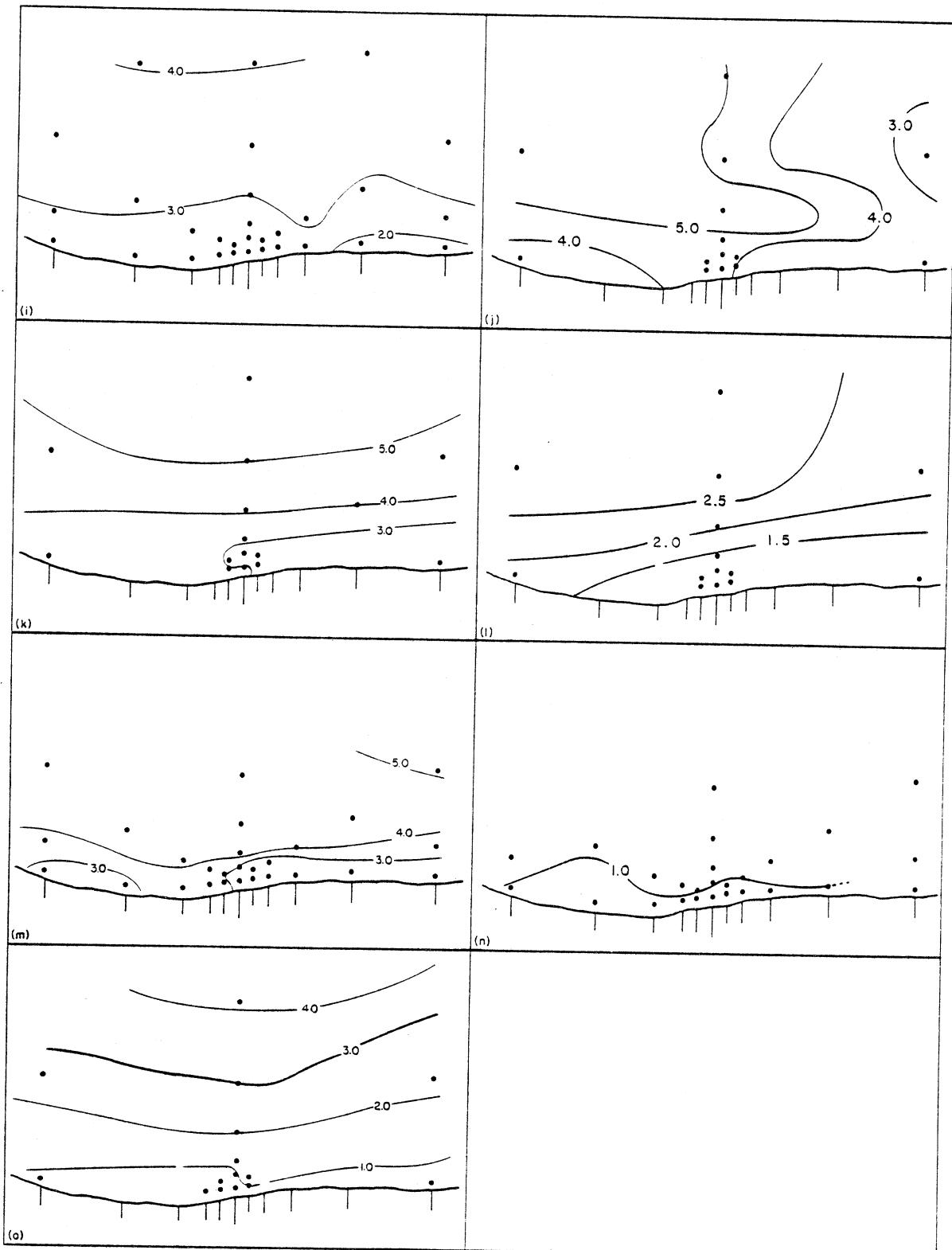


FIG. 4 continued. i) 13 August 1975, j) 11 August 1976, k) 10 September 1975, l) 24 September 1976, m) 17 October 1975, n) 14 October 1976, o) 5 December 1975.

TABLE 2. Zooplankton dry weights ($\mu\text{g}/\text{individual}$ and mg/m^3) derived by the filtration and selection methods for the field survey stations of 17 July 1975.

Station	mg/m^3	FILTRATION		SELECTION	
		$\mu\text{g}/\text{individual}$		mg/m^3	$\mu\text{g}/\text{individual}$
DC-1	56.0	8.5		11.5	1.4
DC-2	52.3	2.1		24.2	1.0
DC-3	86.7	2.3		38.5	1.1
DC-4	205.0	2.2		108.8	1.2
DC-5	225.5	3.0		119.2	1.5
DC-6	112.8	2.5		84.5	2.0
NDC-.5-1	11.0	3.3		6.7	1.2
NDC-.5-2	41.4	2.2		19.6	1.0
NDC-1-1	10.0	1.3		9.5	1.2
NDC-1-2	35.3	1.3		30.3	1.2
NDC-2-1	5.8	0.9		7.8	1.3
NDC-2-3	17.4	0.8		26.3	1.3
NDC-4-1	19.0	1.4		15.6	1.3
NDC-4-3	31.8	0.8		47.4	1.3
NDC-4-4	121.3	3.6		81.5	1.9
NDC-7-1	6.7	0.3		22.8	1.1
NDC-7-3	76.0	1.9		46.8	1.3
NDC-7-5	159.8	1.4		154.0	1.5
SDC-.5-1	27.6	2.3		13.2	1.1
SDC-.5-2	32.1	1.5		24.2	1.1
SDC-1-1	20.0	4.1		6.8	1.4
SDC-1-2	32.8	1.5		25.6	1.0
SDC-2-1	15.6	1.8		10.3	1.0
SDC-2-3	113.1	2.0		59.9	1.0
SDC-4-1	26.2	3.2		7.5	1.0
SDC-4-3	71.7	0.7		113.5	1.1
SDC-4-4	152.4	3.6		59.9	1.8
SDC-7-1	29.8	2.3		14.7	1.2
SDC-7-3	22.5	0.6		47.9	1.2
SDC-7-5	176.4	2.0		116.5	1.3

Zooplankton Abundance and Biomass During the 1975 and 1976 Survey Cruises

Although nearly 40 species of zooplankton were collected over the survey area during 1975 and 1976, only a few were of numerical importance (Table 3). Zooplankton varied in abundance with season with numbers tending to be greatest in the summer months. Zooplankton also varied in abundance over the survey grid with concentrations tending to be lowest in the inshore region in the warmest months of the year. Most of the rarer cyclopoid and cladoceran species and all the harpacticoid species are benthic or epibenthic in habitat, living at the sediment-water interface and rarely encountered in the plankton. Populations of these taxa may be large in the inshore region (Evans and Stewart 1977) and the values shown in Table 3 are underestimates of the true population size of entomostracans for the entire water column and underlying sediments. Our data are more representative of the truly planktonic species and life stages.

Zooplankton abundance and biomass were examined during each cruise in order to determine whether there was any apparent alteration in distributions in the thermal plume region. This was the first step in evaluating the effects of plant operation. For the major survey cruises (April, July, and October), the abundance of total zooplankton, the numerically dominant zooplankton, and total zooplankton dry weight are presented in a series of figures. For the short survey cruises, only figures showing total zooplankton abundance and biomass are presented since these cruises provide minimal information on spatial patterns in zooplankton abundance. Zooplankton data by station are reported in the Appendix (Tables 17-41).

Spring (April, May)

Zooplankton concentrations (Fig. 5) ranged from 3,000 to 15,000/m³ in April 1975 and from 1,000 to 27,000/m³ in April 1976. The numerically dominant taxa were nauplii, immature and adult Cyclops spp. (primarily C. bicuspidatus thomasi), and immature and adult Diaptomus spp. (primarily D. ashlandi). Zooplankton concentrations were not detectably altered in the region of the thermal plume during the April 1975 cruise; the plant was not operational during the April 1976 cruise. Zooplankton biomass in April 1976 ranged from 1 to 29 mg/m³ over the survey grid (Fig. 6). Reliable biomass estimates were not obtained in April 1975 when the selection method was being developed and high concentrations of phytoplankton in the samples prevented the filtration method from being utilized.

Nauplii and immature and adult Cyclops spp. (primarily Cyclops bicuspidatus thomasi) and Diaptomus spp. (primarily D. ashlandi and D. minutus) continued to dominate the May zooplankton. Zooplankton concentrations ranged from 1,000 to 20,000/m³ in 1975 (Fig. 7) and from 600 to 20,000/m³ in 1976. There was no evidence of alterations in zooplankton numbers and composition in the thermal plume in May 1976. Zooplankton

TABLE 3. Mean seasonal density of zooplankton in each of four depth zones during 1975-1976. Spring = April and May; Summer = June, July, and August; Fall = September and October; Winter = December (1975 only). $\text{tr} \leq 0.5/\text{m}^3$.

TAXA	INSHORE ZONE #/m ³ (5-10 m depth)				MIDDLE ZONE #/m ³ (10-20 m depth)			
	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Copepod nauplii	3,656	4,976	2,832	256	6,536	9,209	3,012	264
<u>Cyclops</u> spp. Cl-C5	612	3,341	5,990	14,986	1,308	7,534	8,912	10,896
<u>Cyclops bicuspidatus thomasi</u> C6	381	86	248	1,160	648	333	599	564
<u>Cyclops vernalis</u> C6	0	14	15	4	0	4	12	9
<u>Paracyclops fimbriatus poppei</u> Cl-C6	0	tr	0	0	0	0	tr	0
<u>Mesocyclops edax</u> Cl-C6	0	tr	1	0	0	tr	tr	0
<u>Eucyclops</u> spp. Cl-C6	tr	1	4	0	tr	0	1	0
<u>Tropocyclops prasinus mexicanus</u> Cl-C6	5	896	1,511	864	7	1,613	3,008	861
<u>Diaptomus</u> spp. Cl-C5	735	2,286	2,542	2,531	1,845	5,103	6,654	2,719
<u>Diaptomus ashlandi</u> C6	625	19	50	1,576	1,085	61	294	1,589
<u>Diaptomus minutus</u> C6	45	1,024	201	1,502	87	1,717	385	1,621
<u>Diaptomus oregonensis</u> C6	64	22	58	4,719	78	76	125	3,439
<u>Diaptomus sicilis</u> C6	77	2	tr	205	142	4	1	357
<u>Epischura lacustris</u> Cl-C6	37	132	332	33	37	222	330	30
<u>Eurytemora affinis</u> Cl-C6	13	1,232	742	8	9	1,209	432	14
<u>Limnocalanus macrurus</u> Cl-C6	87	2	0	1	202	3	tr	6
<u>Senecilia calanoides</u> Cl-C6	0	0	0	9	0	0	0	0
Harpacticoids	tr	3	2	3	1	tr	tr	3
<u>Bosmina longirostris</u>	97	19,761	17,117	386	223	16,076	9,222	140
<u>Eubosmina coregoni</u>	2	492	10,883	2,333	3	869	10,281	1,085
<u>Daphnia retrocurva</u>	3	1,087	993	151	4	2,512	2,627	108
<u>Daphnia galeata mendotae</u>	tr	68	153	73	tr	199	316	38
<u>Daphnia longiremus</u>	tr	0	0	0	tr	0	0	0
<u>Ceriodaphnia</u> spp.	tr	138	5	0	1	71	14	0
<u>Alona</u> spp.	1	8	4	0	1	0	5	0
<u>Chydorus sphaericus</u>	6	27	117	1	5	7	28	0
<u>Disparalona rostrata</u>	0	tr	1	0	0	0	0	0
<u>Diaphanosoma</u> spp.	tr	499	475	1	tr	2,088	667	0
<u>Macrothrix laticornis</u>	tr	0	6	0	tr	0	7	0
<u>Leydigia quadrangularis</u>	0	0	2	0	0	0	1	0
<u>Eury cercus lamellatus</u>	tr	2	2	0	tr	0	1	0
<u>Ilyocryptus</u> spp.	tr	tr	tr	0	tr	0	0	0
<u>Latona setifera</u>	0	tr	0	0	0	0	0	0
<u>Sida crystallina</u>	0	tr	tr	0	0	0	0	0
<u>Polyphemus pediculus</u>	0	138	14	0	0	177	13	0
<u>Holopedium gibberum</u>	0	78	80	1	1	227	110	0
<u>Leptodora kindtii</u>	0	43	79	1	tr	70	78	0
<u>Asplanchna</u> spp.	8	2,743	324	67	12	2,319	388	43
Total Zooplankton	6,451	38,981	44,775	30,860	12,079	38,335	47,528	23,782

TABLE 3 continued.

TAXA	INNER OFFSHORE ZONE #/m ³ (20-30 m depth)				OUTER OFFSHORE ZONE #/m ³ (30-45 m depth)			
	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Copepod nauplii	6,295	5,060	2,719	743	4,044	4,382	4,482	633
<u>Cyclops</u> spp. C1-C5	2,153	10,922	9,158	9,581	684	6,297	9,629	2,841
<u>Cyclops bicuspidatus thomasi</u> C6	641	2,734	859	273	557	3,769	1,625	65
<u>Cyclops vernalis</u> C6	1	14	8	2	3	6	0	1
<u>Paracyclops fimbriatus poppei</u> C1-C6	tr	0	1	0	0	0	0	0
<u>Mesocyclops edax</u> C1-C6	tr	1	2	0	0	1	0	0
<u>Eucyclops</u> spp. C1-C6	tr	1	0	0	0	0	0	0
<u>Tropocyclops prasinus mexicanus</u> C1-C6	7	823	2,826	362	5	504	3,079	109
<u>Diaptomus</u> spp. C1-C5	3,039	11,579	9,944	1,801	2,031	11,629	7,398	564
<u>Diaptomus ashlandi</u> C6	1,014	1,167	304	1,601	876	1,274	965	492
<u>Diaptomus minutus</u> C6	117	1,039	567	810	87	739	208	245
<u>Diaptomus oregonensis</u> C6	87	247	214	1,352	58	244	273	299
<u>Diaptomus sicilis</u> C6	163	29	14	410	109	98	30	486
<u>Epischura lacustris</u> C1-C6	8	148	618	4	0	67	137	0
<u>Eurytemora affinis</u> C1-C6	6	483	189	0	2	122	0	0
<u>Limnocalanus macrurus</u> C1-C6	357	33	0	10	164	191	22	22
<u>Seneccella calanoides</u> C1-C6	0	0	0	0	0	1	0	0
Harpacticoids	6	1	1	0	0	1	0	0
<u>Bosmina longirostris</u>	128	21,009	1,772	19	11	5,276	598	14
<u>Eubosmina coregoni</u>	3	959	5,722	168	0	658	347	71
<u>Daphnia retrocurva</u>	15	3,127	2,859	6	1	2,737	1,816	4
<u>Daphnia galeata mendotae</u>	4	273	897	9	tr	414	654	5
<u>Daphnia longiremus</u>	1	0	0	0	0	0	0	0
<u>Ceriodaphnia</u> spp.	tr	102	1	0	0	16	5	0
<u>Alona</u> spp.	tr	0	3	0	0	0	0	0
<u>Chydorus sphaericus</u>	2	4	5	0	0	4	0	0
<u>Disparalona rostrata</u>	0	0	0	0	0	0	0	0
<u>Diaphanosoma</u> spp.	0	750	390	7	1	788	410	0
<u>Macrothrix laticornis</u>	0	0	0	0	0	0	0	0
<u>Leydigia quadrangularis</u>	0	0	0	0	0	0	0	0
<u>Eurycercus lamellatus</u>	0	1	0	0	0	0	0	0
<u>Ilyocryptus</u> spp.	0	0	0	0	0	0	0	0
<u>Latona setifera</u>	0	0	0	0	0	0	0	0
<u>Sida crystallina</u>	0	0	0	0	0	tr	0	0
<u>Polyphemus pediculus</u>	0	87	6	0	0	52	0	0
<u>Holopedium gibberum</u>	2	178	47	0	0	133	0	0
<u>Leptodora kindtii</u>	0	59	48	0	0	39	20	0
<u>Asplanchna</u> spp.	12	1,307	499	6	1	708	162	0
Total Zooplankton	14,056	48,144	39,660	17,162	8,568	38,706	38,581	5,851

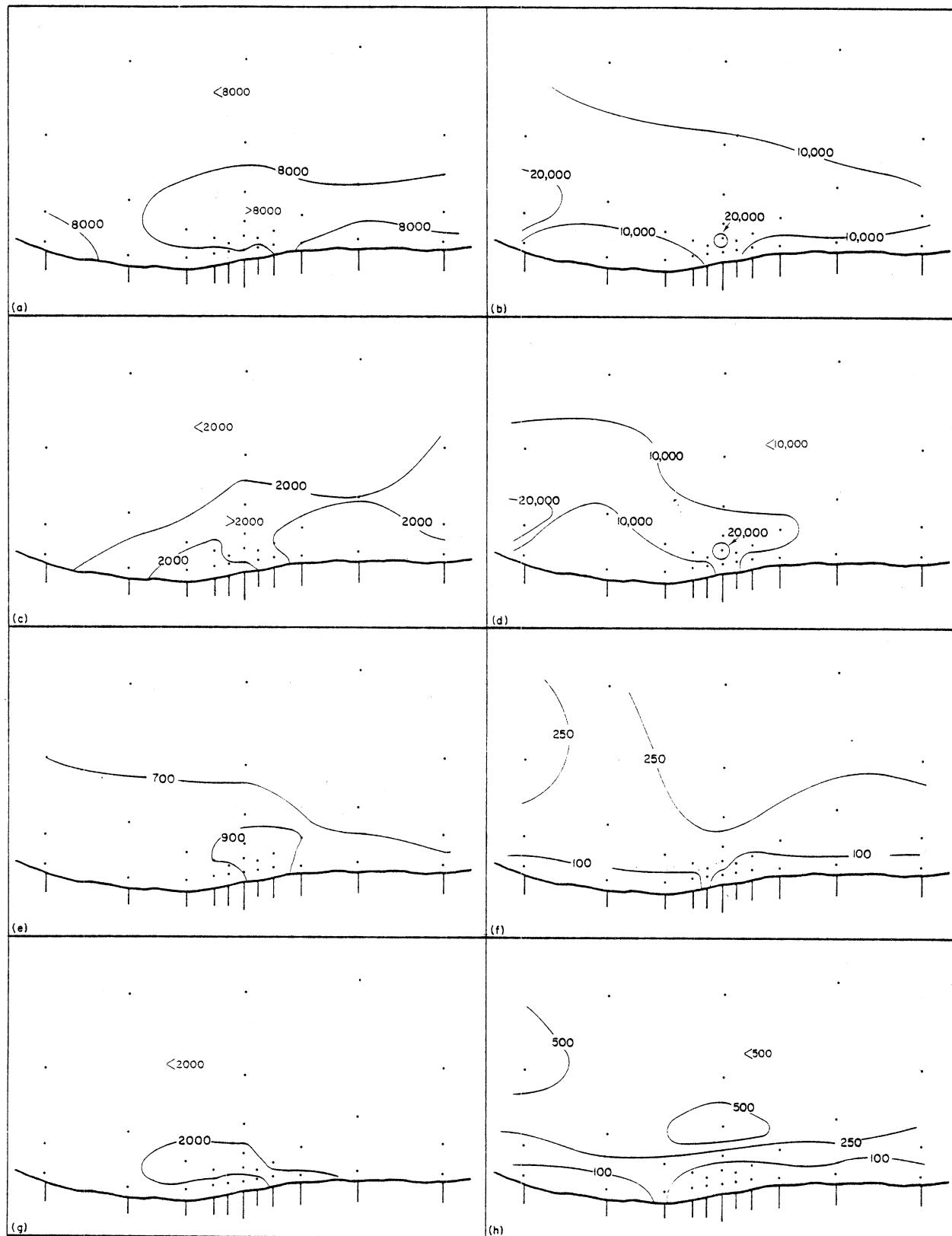


FIG. 5. Horizontal distributions (number/m³) of total zooplankton and major zooplankton taxa collected on 17 April 1975 (left column) and 14 April 1976 (right column). a,b) Total zooplankton, c,d) copepod nauplii, e,f) Cyclops spp. C1-C5, g,h) Cyclops spp. C6.

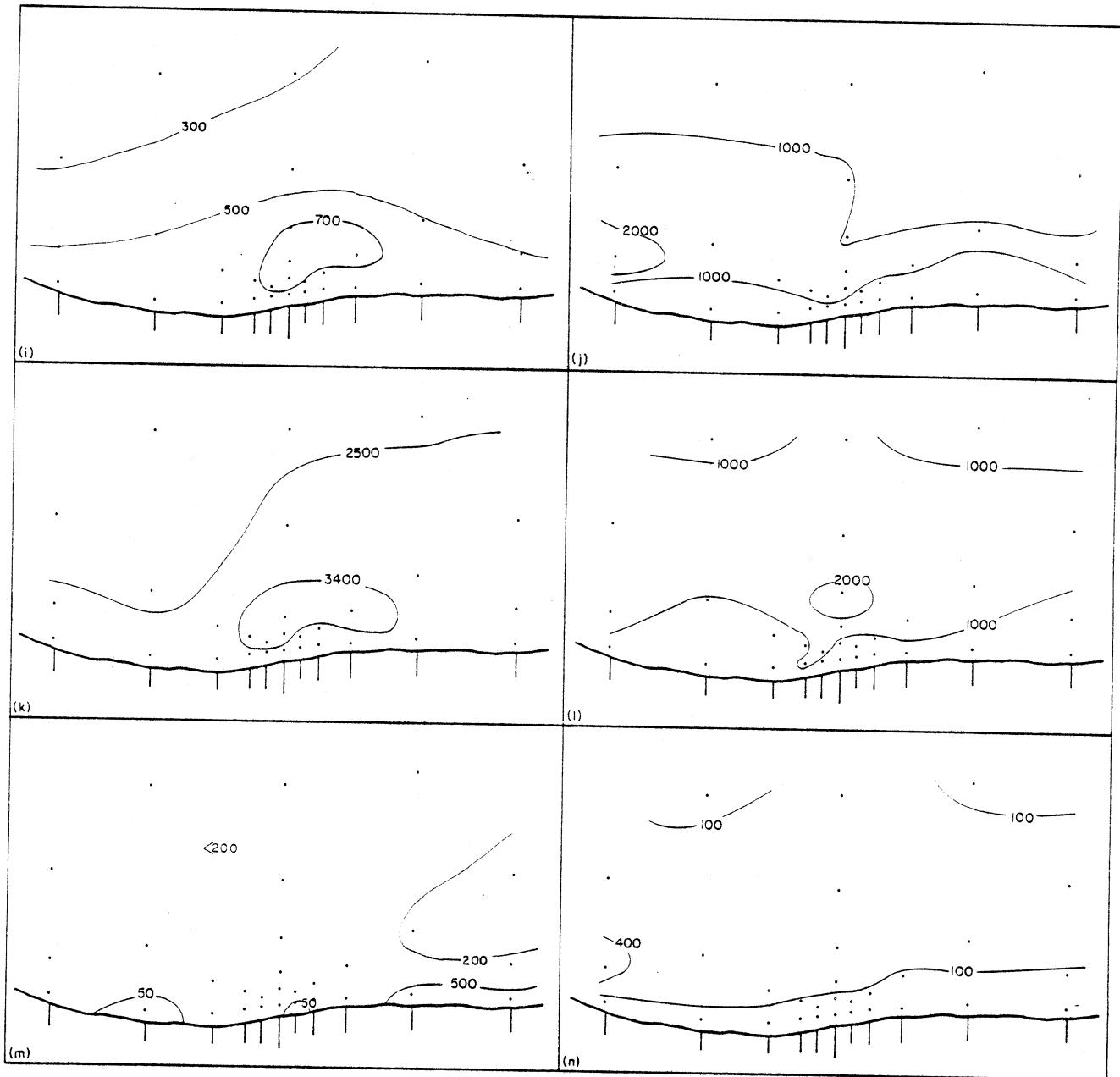


FIG. 5 continued. i,j) *Diaptomus* spp. C1-C5, k,l) *Diaptomus* spp. C6, m,n) *Limnocalanus macrurus* C1-C6.

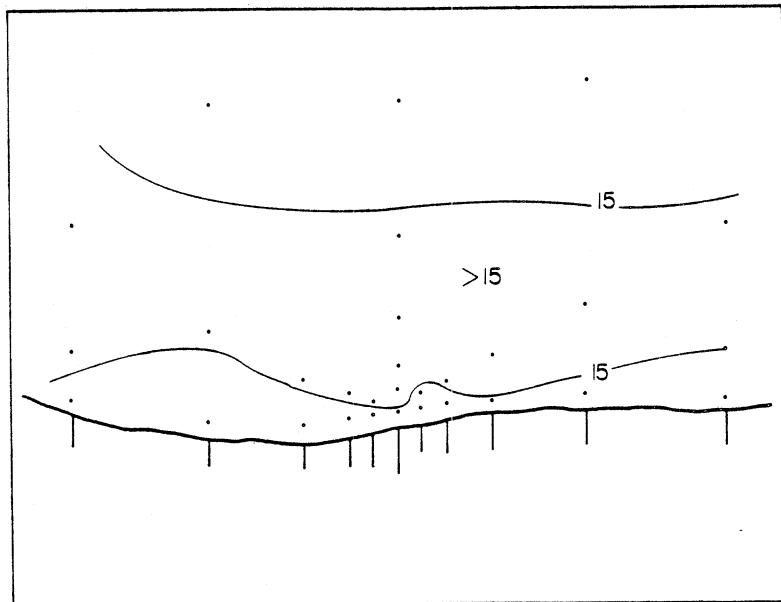


FIG. 6. The standing stock of zooplankton ($\text{mg dry wt}/\text{m}^3$) on 14 April 1976.

biomass in May 1976 ranged from 1 to 37 mg/m^3 over the survey grid (Fig. 8).

Summer (June, July, August)

Copepods (*Cyclops bicuspidatus thomasi*, *Diaptomus ashlandi*, *D. minutus*) continued to dominate the June zooplankton, although the cladoceran *Bosmina longirostris* and the copepod *Eurytemora affinis* were relatively abundant at the stations closest to shore, particularly in 1976. Zooplankton concentrations (Fig. 9) were higher in June 1976 (31,000 to 104,000/ m^3) than in 1975 (7,000 to 50,000/ m^3). Zooplankton biomass ranged from 9 to 85 mg/m^3 in 1975 and from 47 to 130 mg/m^3 in 1976 (Fig. 10).

Total zooplankton concentrations (Fig. 11) were similar in July 1975 ($5,000$ to $103,000/\text{m}^3$) and 1976 ($32,000$ to $152,000/\text{m}^3$). The numerically dominant taxon was *Bosmina longirostris*. Immature *Diaptomus* spp. and *Cyclops* spp. copepodites were of secondary importance in both years. Immature *Eurytemora affinis* copepodites and *Asplanchna* spp. were relatively abundant at several stations within a few kilometers of shore. There was no evidence of altered zooplankton distributions in the region of the thermal plume during the July 1976 cruise; the plant was not operational during the July 1975 cruise. However, in both years *Asplanchna* spp. populations were greatest at DC-2, a few hundred meters offshore of the discharge jets. Zooplankton biomass ranged from 8 to 154 mg/m^3 in 1975 and from 42 to 106 mg/m^3 in 1976 (Fig. 12).

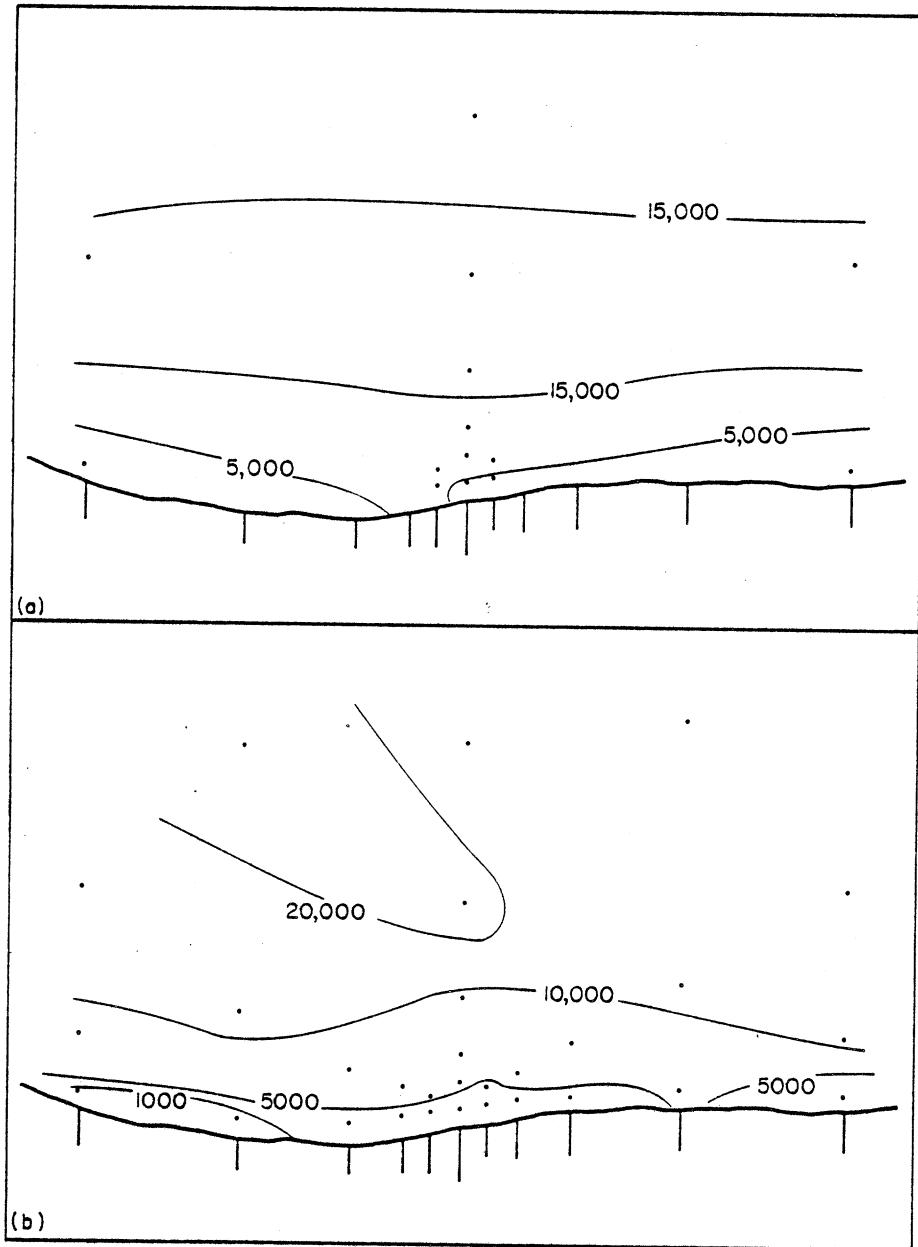


FIG. 7. The horizontal distribution (number/m^3) of total zooplankton collected on a) 15 May 1975, b) 12 May 1976.

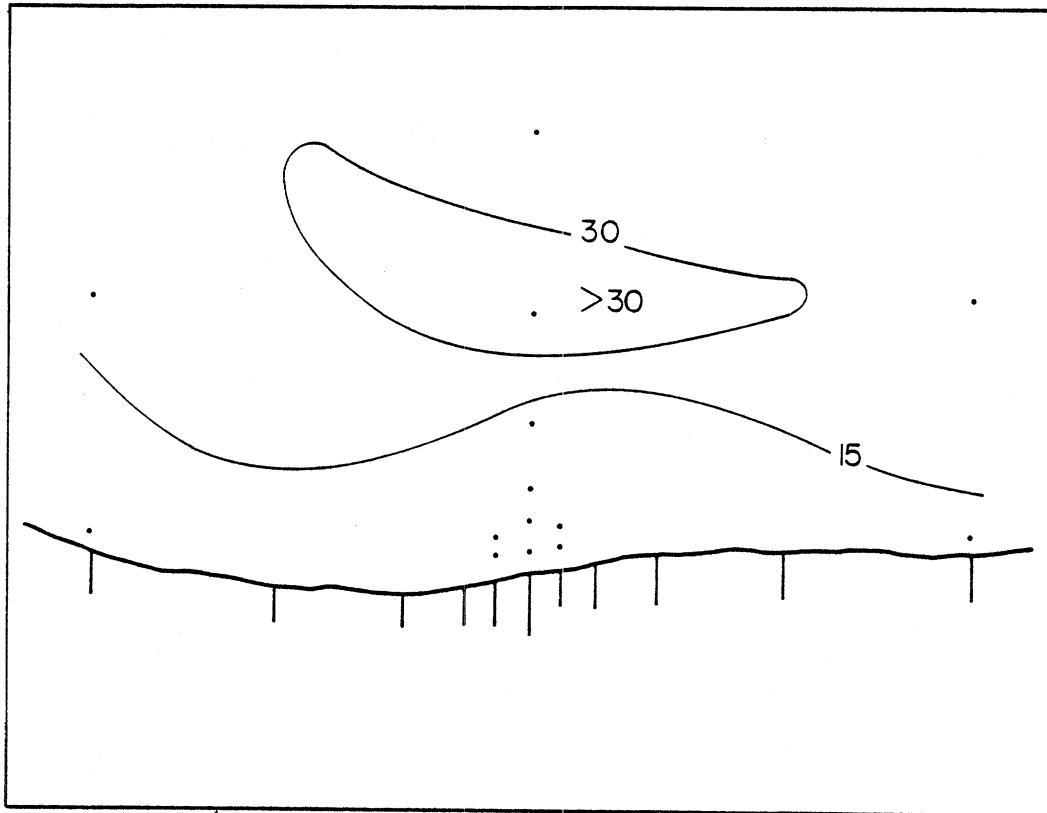


FIG. 8. The standing stock of zooplankton (mg dry wt/m^3) on 12 May 1976.

In August several taxa formed significant (greater than 10%) components of the zooplankton. Among the copepods, nauplii, immature and adult Diaptomus spp. (primarily D. ashlandi and D. minutus) and immature and adult Cyclops spp. (primarily C. bicuspidatus thomasi) were the dominant forms in both years. Daphnia spp. (primarily D. retrocurva) and Bosmina longirostris were the dominant cladocerans in August of both years while in 1976 Diaphanosoma leuchtenbergianum was a significant component of the zooplankton at several stations. Total zooplankton concentrations (Fig. 13) were similar in August 1975 (10,000 to $84,000/\text{m}^3$) and 1976 (14,000 to $72,000/\text{m}^3$) as was zooplankton biomass (15 to 82 mg/m^3 , 11 to 78 mg/m^3 respectively) (Fig. 14).

Autumn (September, October)

Nauplii, immature Cyclops spp. and Diaptomus spp. copepodites, and Bosmina longirostris dominated the September 1975 and 1976 zooplankton. Daphnia retrocurva and Tropocyclops prasinus mexicanus were also numerically important components of the September 1975 zooplankton while Eubosmina coregoni was important in 1976. Total zooplankton concentrations (Fig. 15) were greater in 1975 (37,000 to $110,000/\text{m}^3$) than in 1976 (24,000 to $55,000/\text{m}^3$) as was zooplankton biomass (26 to 103 mg/m^3 , 22 to 55 mg/m^3 respectively) (Fig. 16).

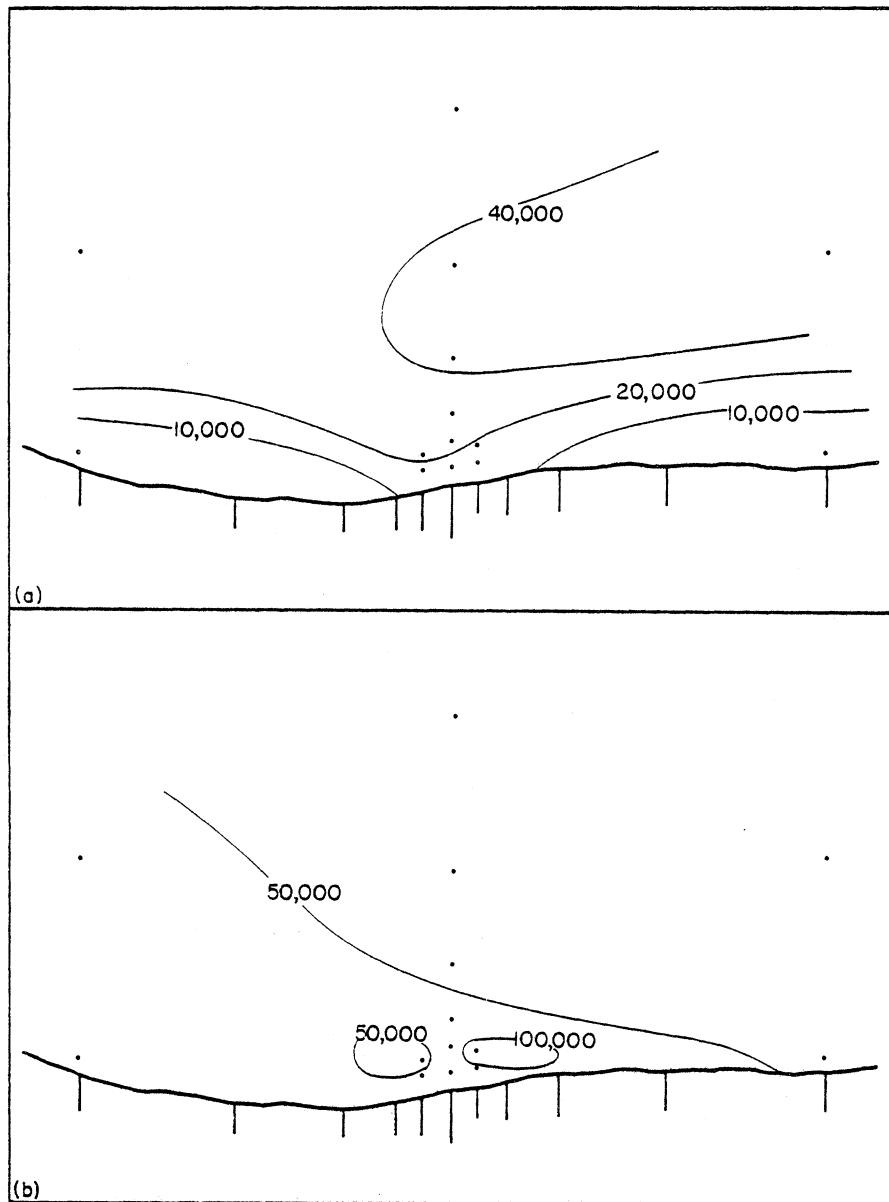


FIG. 9. The horizontal distribution of total zooplankton collected on a) 12 June 1975, b) 17 June 1976.

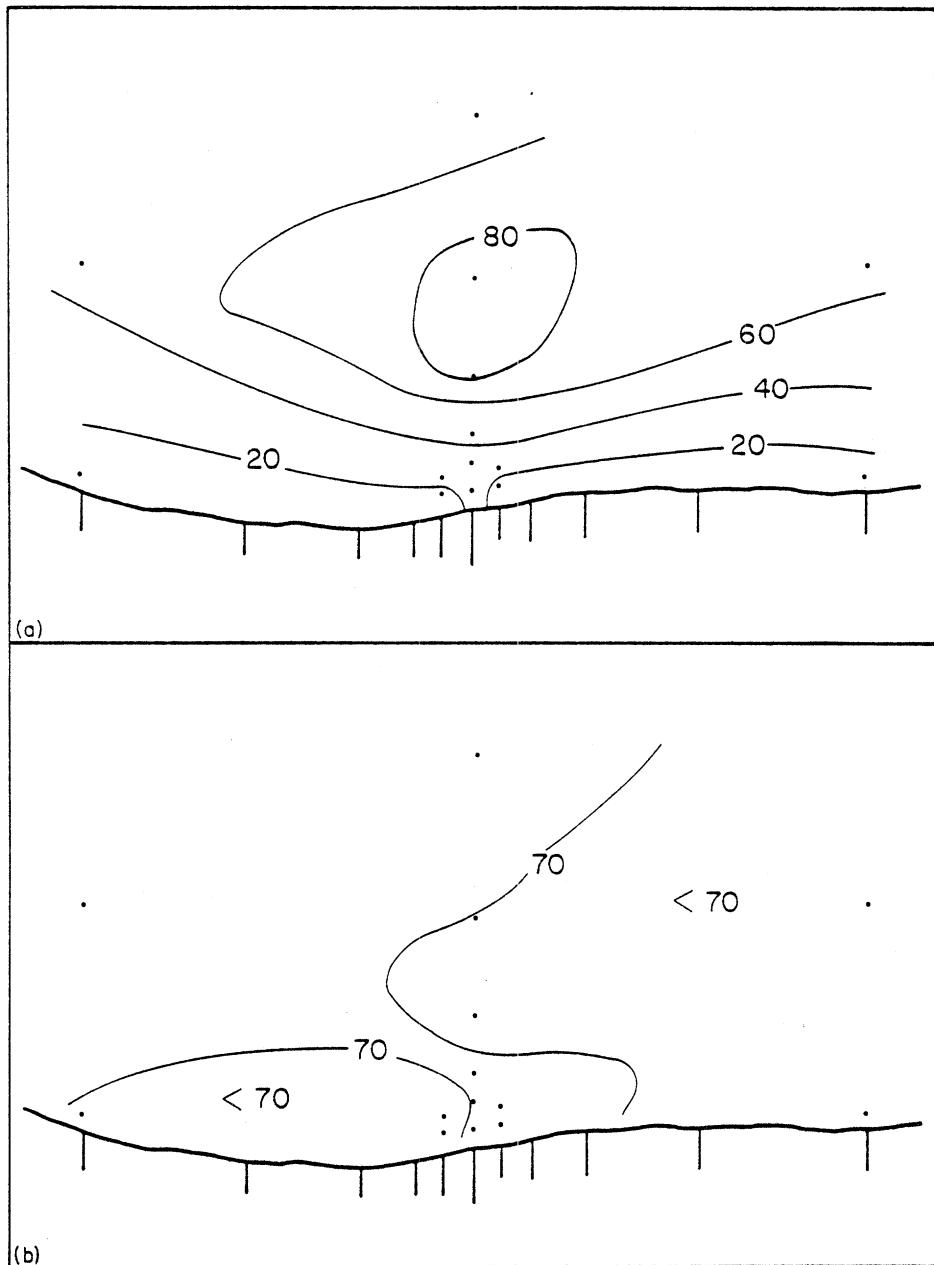


FIG. 10. The standing stock of zooplankton (mg dry wt/m^3) on
 a) 12 June 1975, b) 17 June 1976.

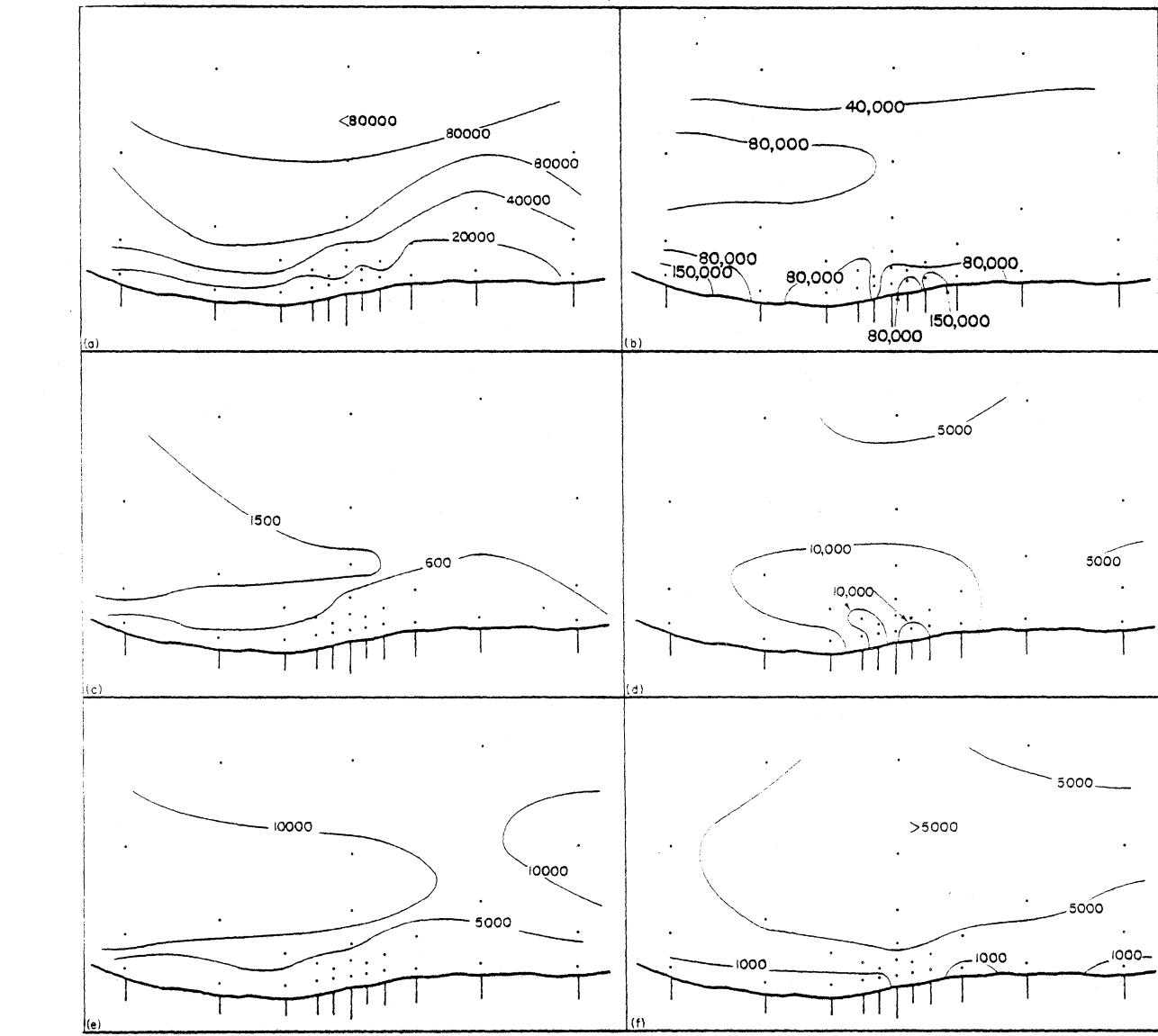


FIG. 11. Horizontal distributions (number/m^3) of total zooplankton and major taxa collected on 17 July 1975 (left column) and 15 July 1976 (right column). a,b) total zooplankton, c,d) copepod nauplii, e,f) Cyclops spp. C1-C5.

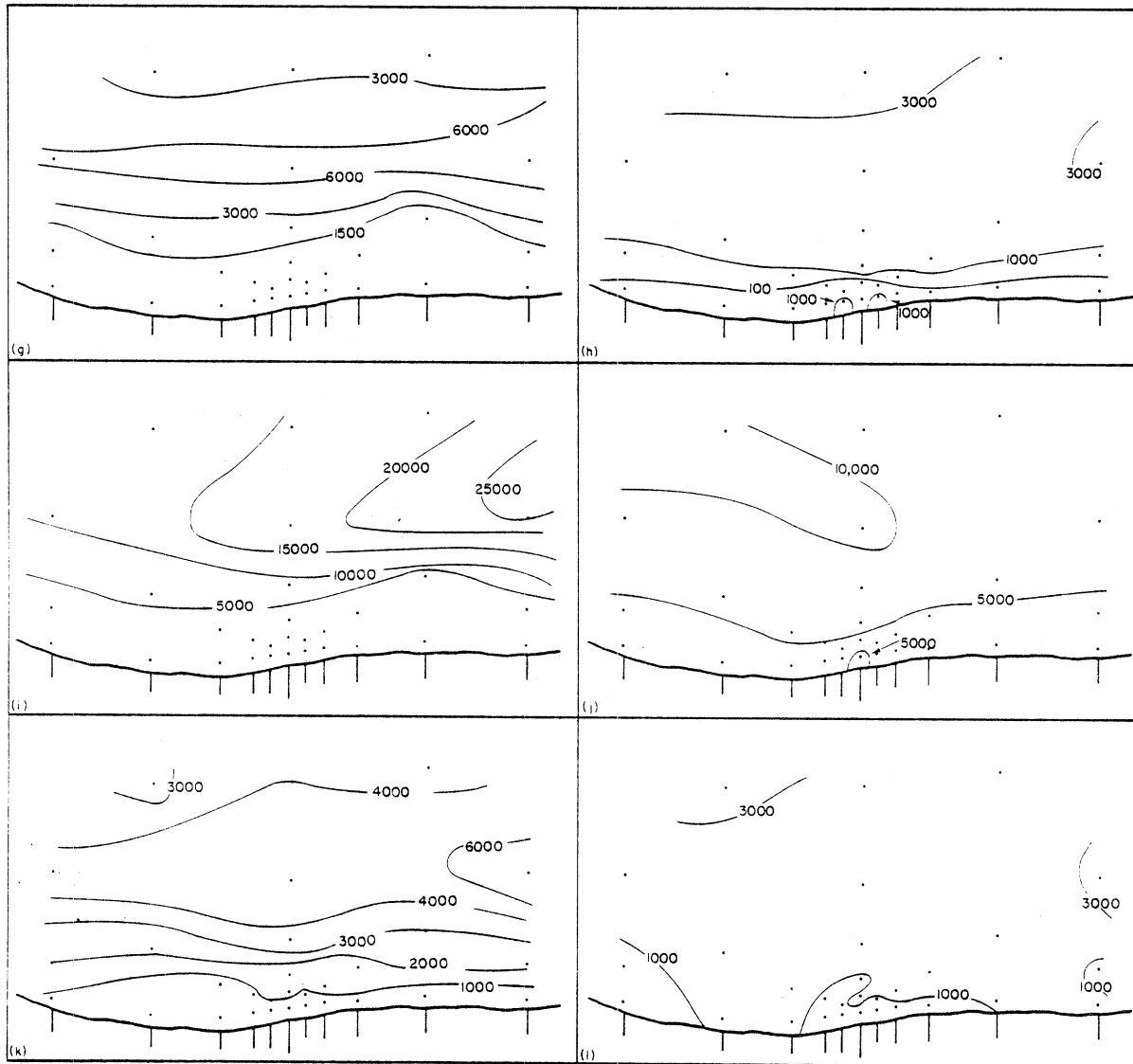


FIG. 11 continued. g,h) Cyclops spp. C6, i,j) Diaptomus spp. C1-C5, k,l) Diaptomus spp. C6.

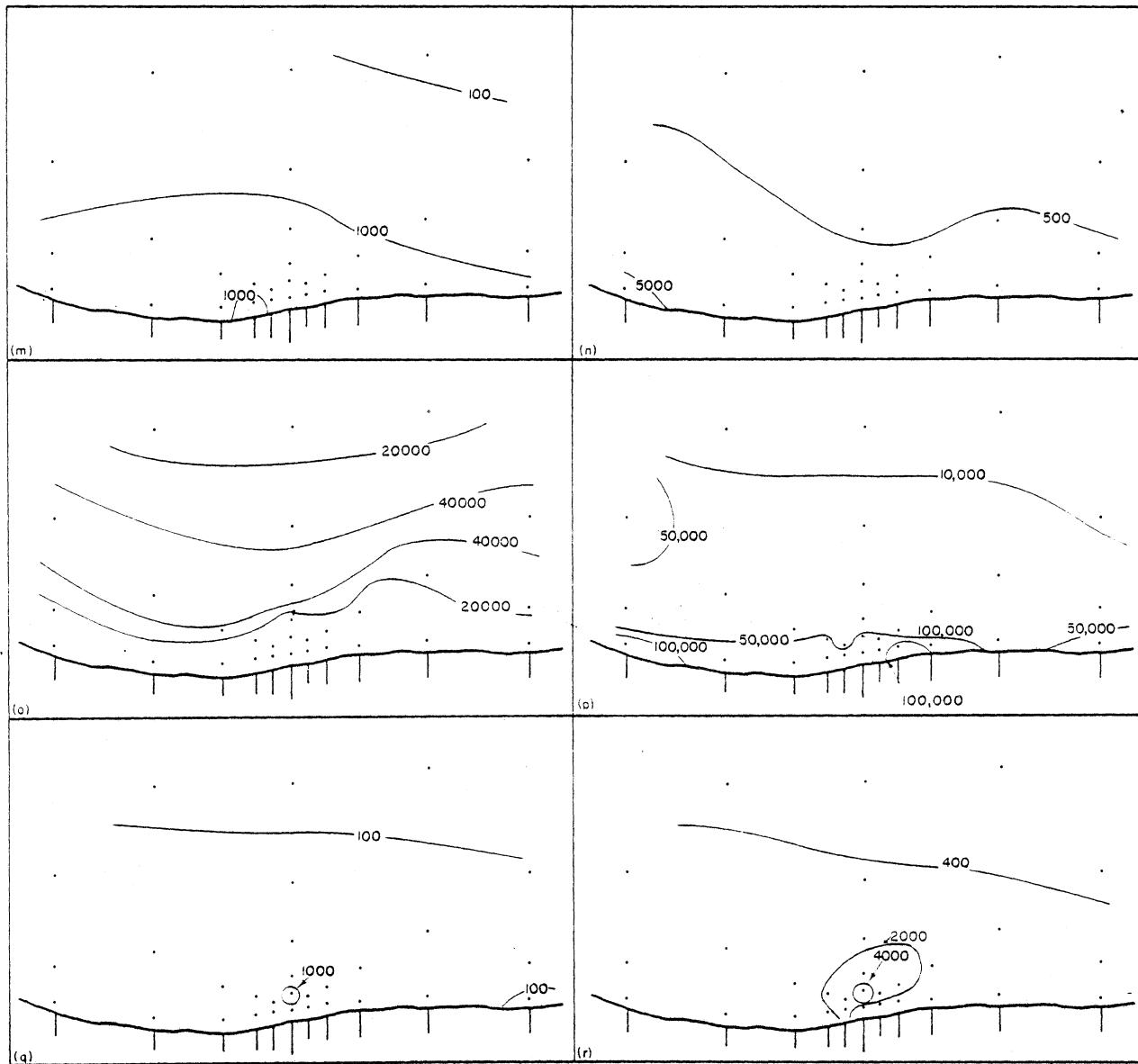


FIG. 11 continued. m,n) Eurytemora affinis C1-C6, o,p) Bosmina longirostris, and q,r) Asplanchna spp.

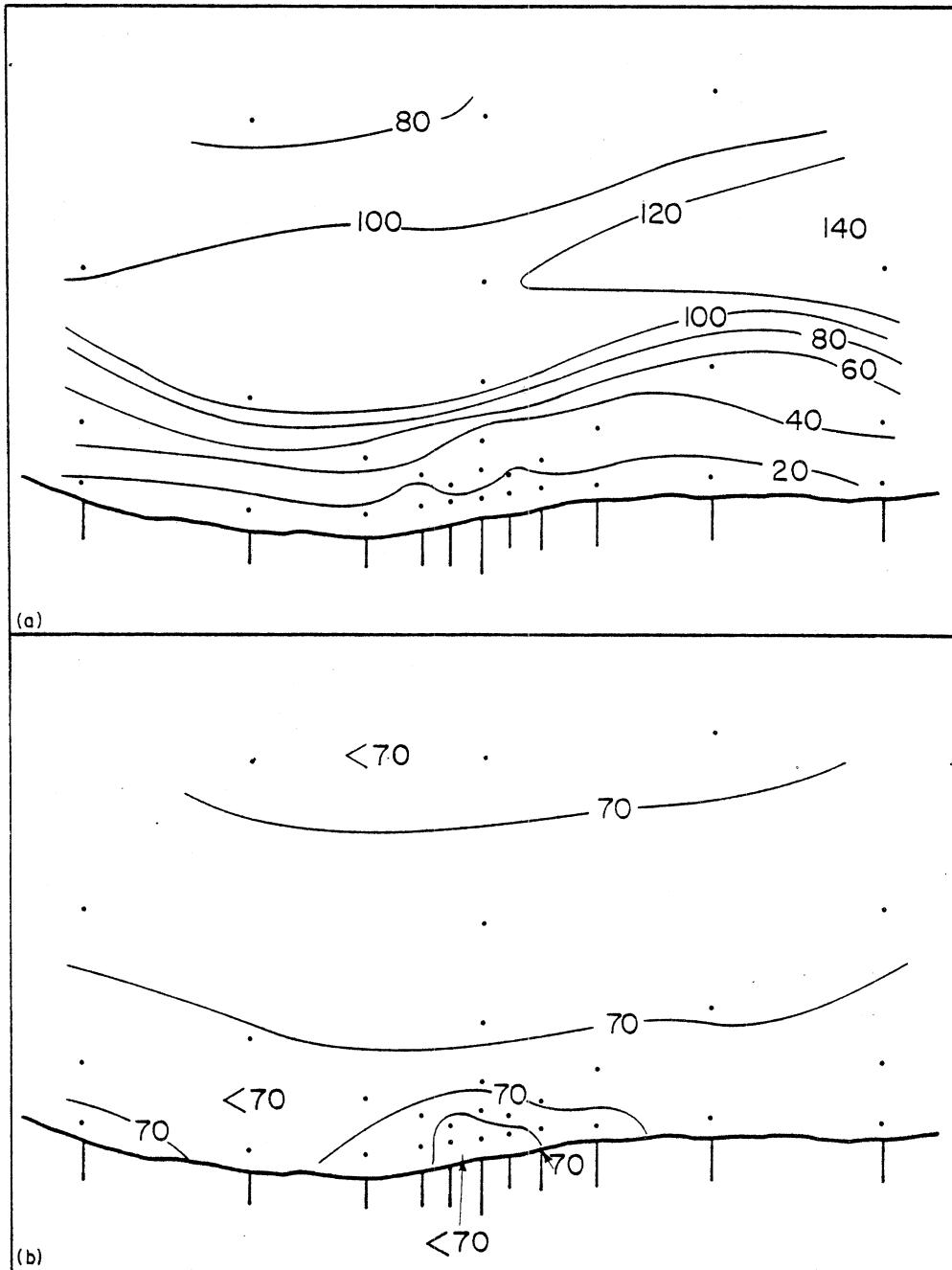


FIG. 12. The standing stock of zooplankton (mg dry weight/m³) on a) 17 July 1975, b) 15 July 1976.

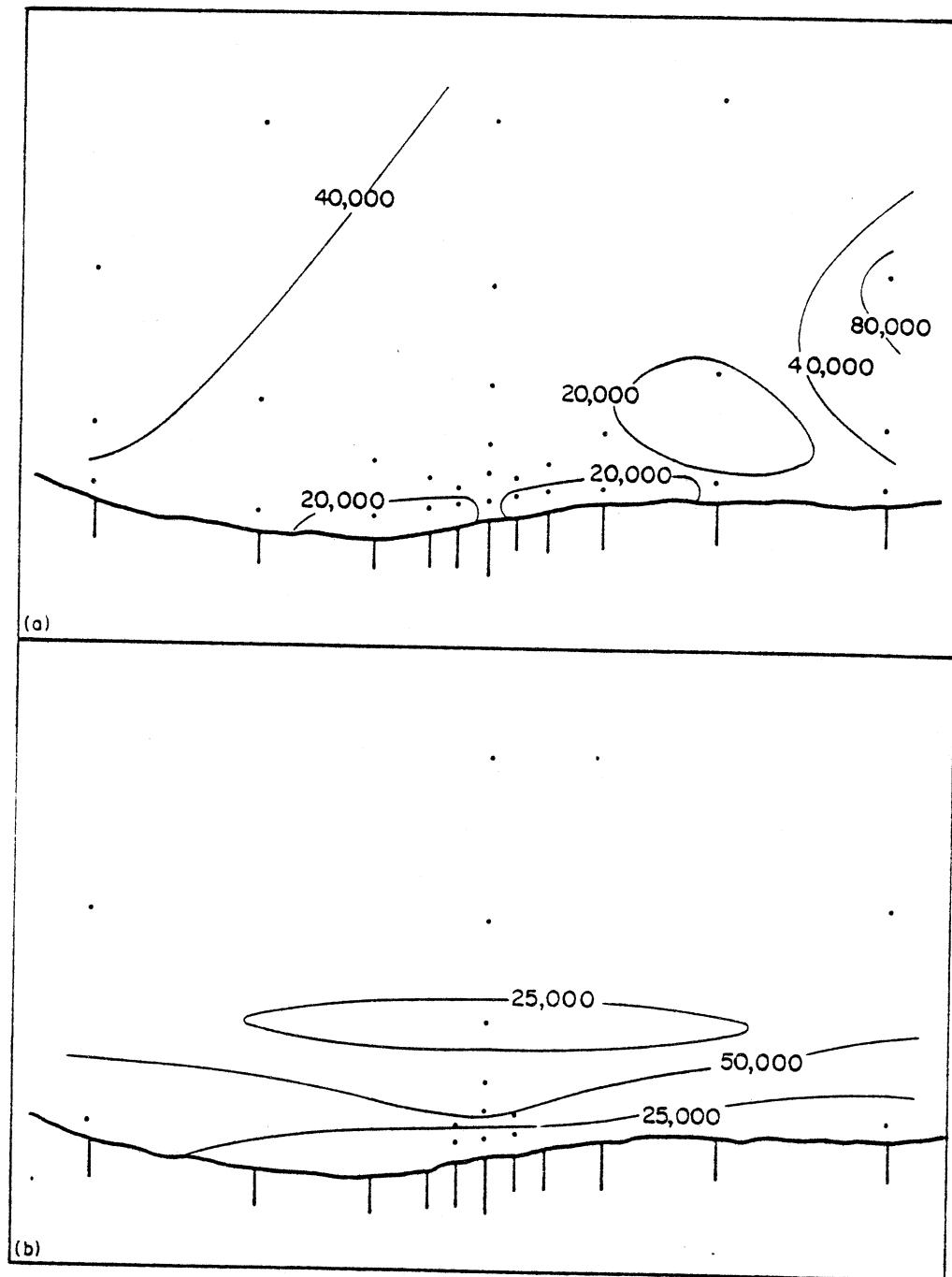


FIG. 13. The horizontal distribution of total zooplankton (number/m^3) collected on a) 13 August 1975, b) 11 August 1976.

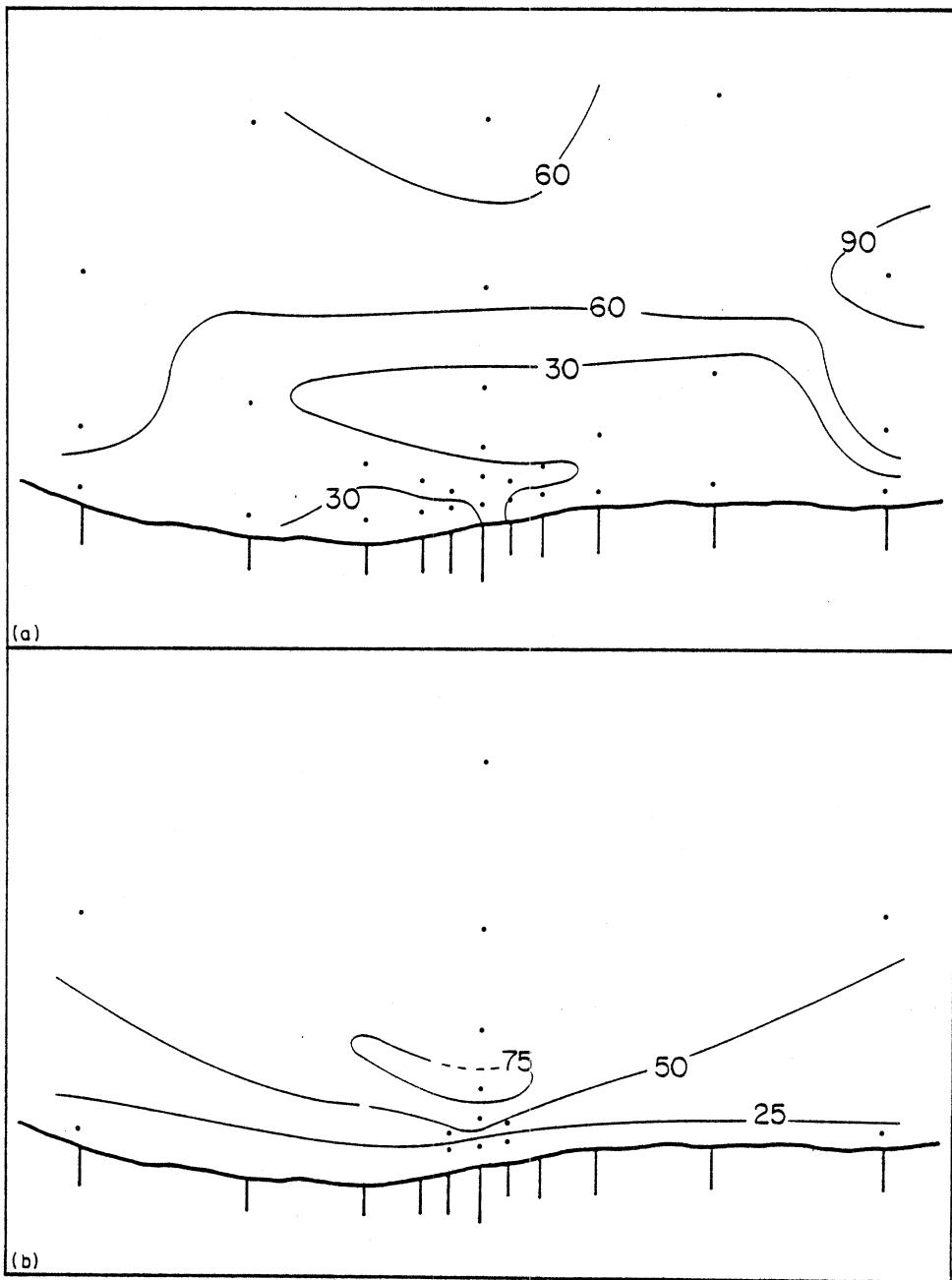


FIG. 14. The standing stock of zooplanton (mg dry weight/m³) on a) 13 August 1975, b) 11 August 1976.

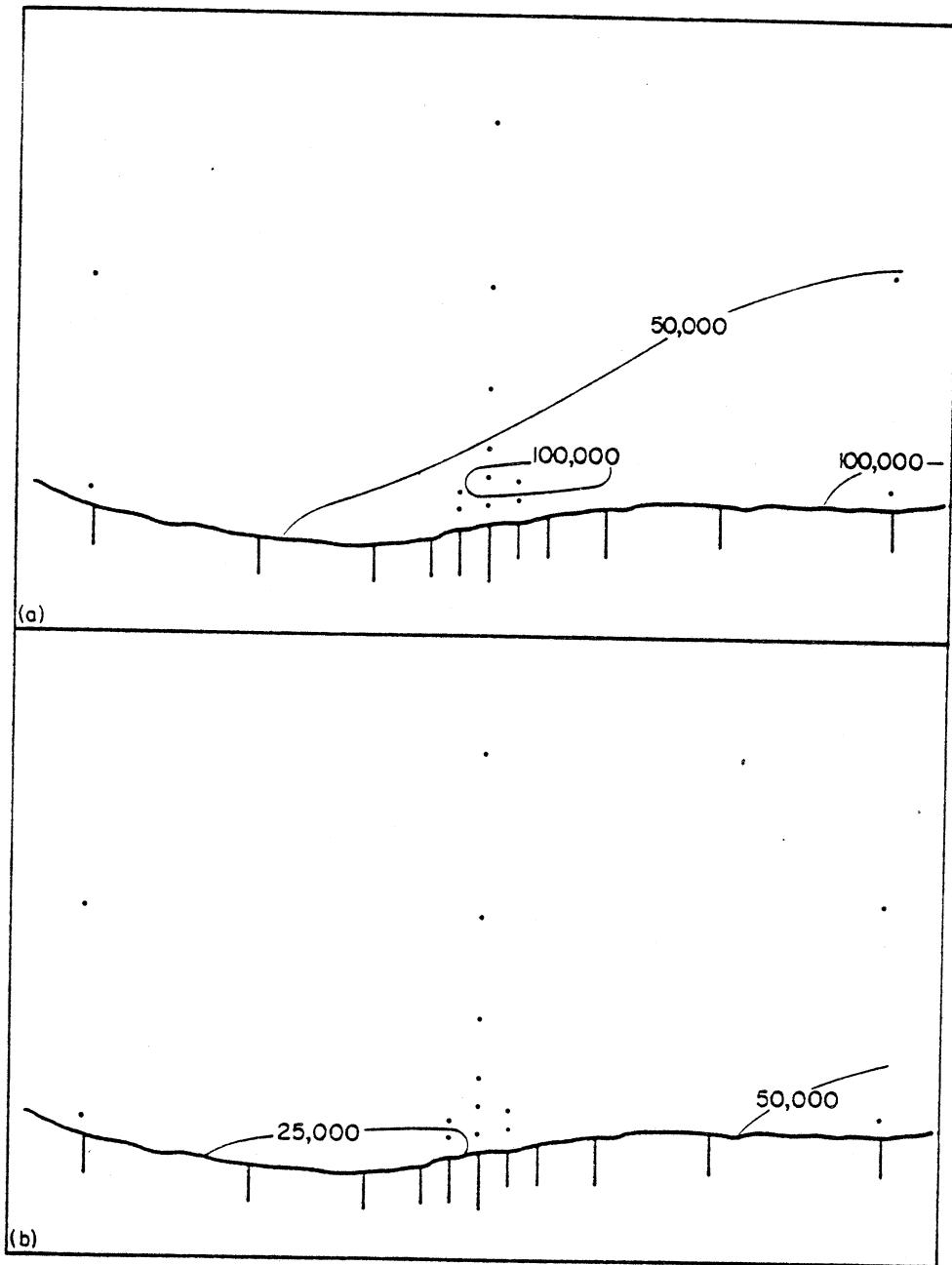


FIG. 15. The horizontal distribution of total zooplankton (number/m^3) collected on a) 10 September 1975, b) 24 September 1976.

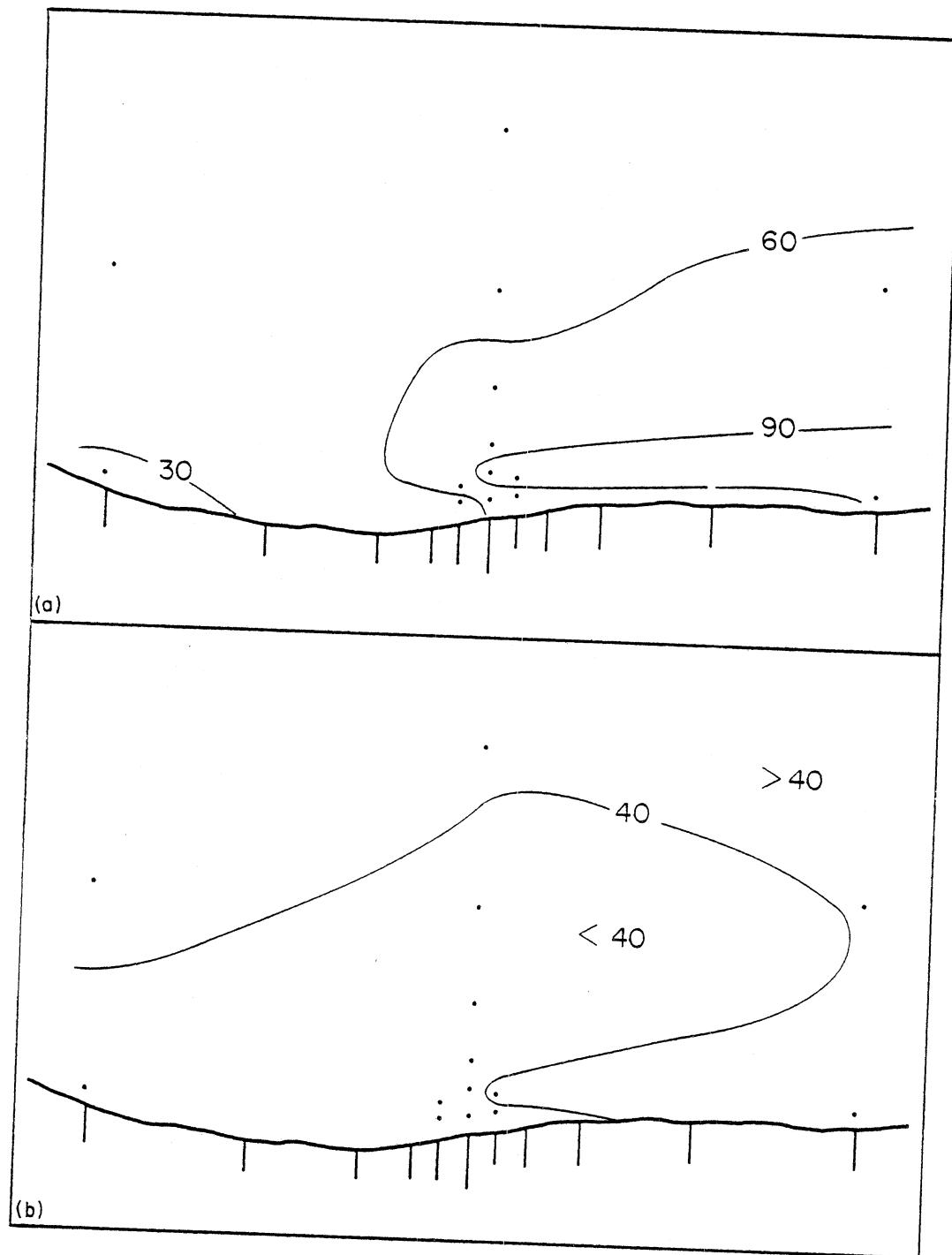


FIG. 16. The standing stock of zooplankton (mg dry weight/m³) on a) 10 September 1975, b) 24 September 1976.

Eubosmina coregoni, Bosmina longirostris, nauplii, and immature Cyclops spp. and Diaptomus spp. were the major components of the October zooplankton (Fig. 17). Daphnia spp. were of secondary importance. Total zooplankton concentrations were lower in 1975 (9,000 to 45,000/m³) than in 1976 (31,000 to 81,000/m³). Zooplankton distributions were not detectably altered in the region of the thermal plume. Zooplankton biomass ranged from 12 to 60 mg/m³ in 1975 and from 40 to 102 mg/m³ in 1976 (Fig 18).

Winter (December)

The December 1975 zooplankton were numerically dominated by immature Cyclops spp. (primarily C. bicuspis datus thomasi) and by immature and adult Diaptomus spp. copepodites (primarily D. ashlandi, minutus, and oregonensis). Nauplii were numerous at some stations. Zooplankton abundances ranged from 6,000 to 43,000/m³ over the survey grid (Fig. 19) and biomass from 29 to 124 mg/m³ (Fig. 20). There was no evidence of altered zooplankton populations in the region of the thermal plume.

Principal Component Analysis with an Emphasis on the 1975 and 1976 Analyses

A total of 16 analyses were performed utilizing the major survey data from the April, July, and October major cruises (1972 to 1976) and the December 1975 short survey data. In 1975 and 1976, the first principal component accounted for 54 to 92% of the total variance while the second principal component accounted for an additional 5 to 21% of the variance (Table 4). Similar values were obtained with the preoperational data sets.

The first principal component (PC1) was correlated with depth. For most analyses, the correlation was positive and stations in shallow water had lower PC1 values than stations located in deeper waters. Ordination of stations by their PC1 and PC2 (second principal component) values generally separated the stations into three depth-related groups. The boundaries between the inshore and middle group fluctuated between the 7 to 10-m depth contours but occurred most frequently at the 10-m depth contour. The boundary between the middle and offshore group fluctuated between the 17 and 21-m depth contours but occurred most frequently at the 20-m depth contour. Variations in the boundaries of the region are to be expected since lake currents vary in speed and direction from month to month. From these analyses, we conclude that the 10 and 20-m contours can be used as approximate boundaries for the inshore, middle, and offshore regions.

The second principal component was not identified. It was occasionally correlated with water depth, surface water temperature, or Secchi disc depth but the correlations were generally not high and were not consistent from month to month. Stations with similar geographic locations did not have similar PC1 and PC2 values. There was no evidence that zooplankton populations in the northern half of the survey grid were distinct from populations in the south.

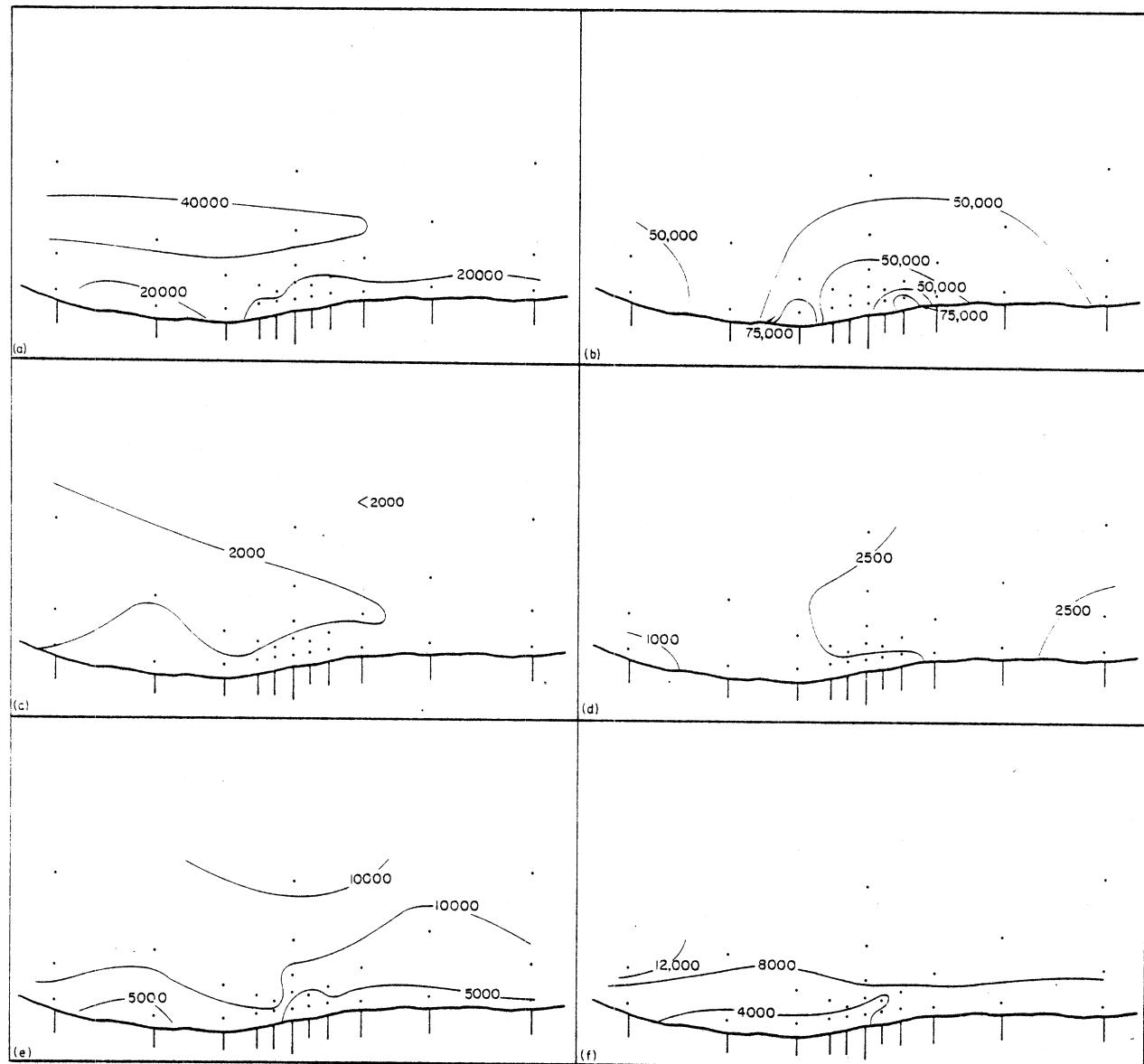


FIG. 17. Horizontal distribution (number/m³) of total zooplankton and major taxa collected on 17 October 1975 (left column) and 14 October 1976 (right column). a,b) Total zooplankton, c,d) copepod nauplii, e,f) Cyclops spp. C1-C5.

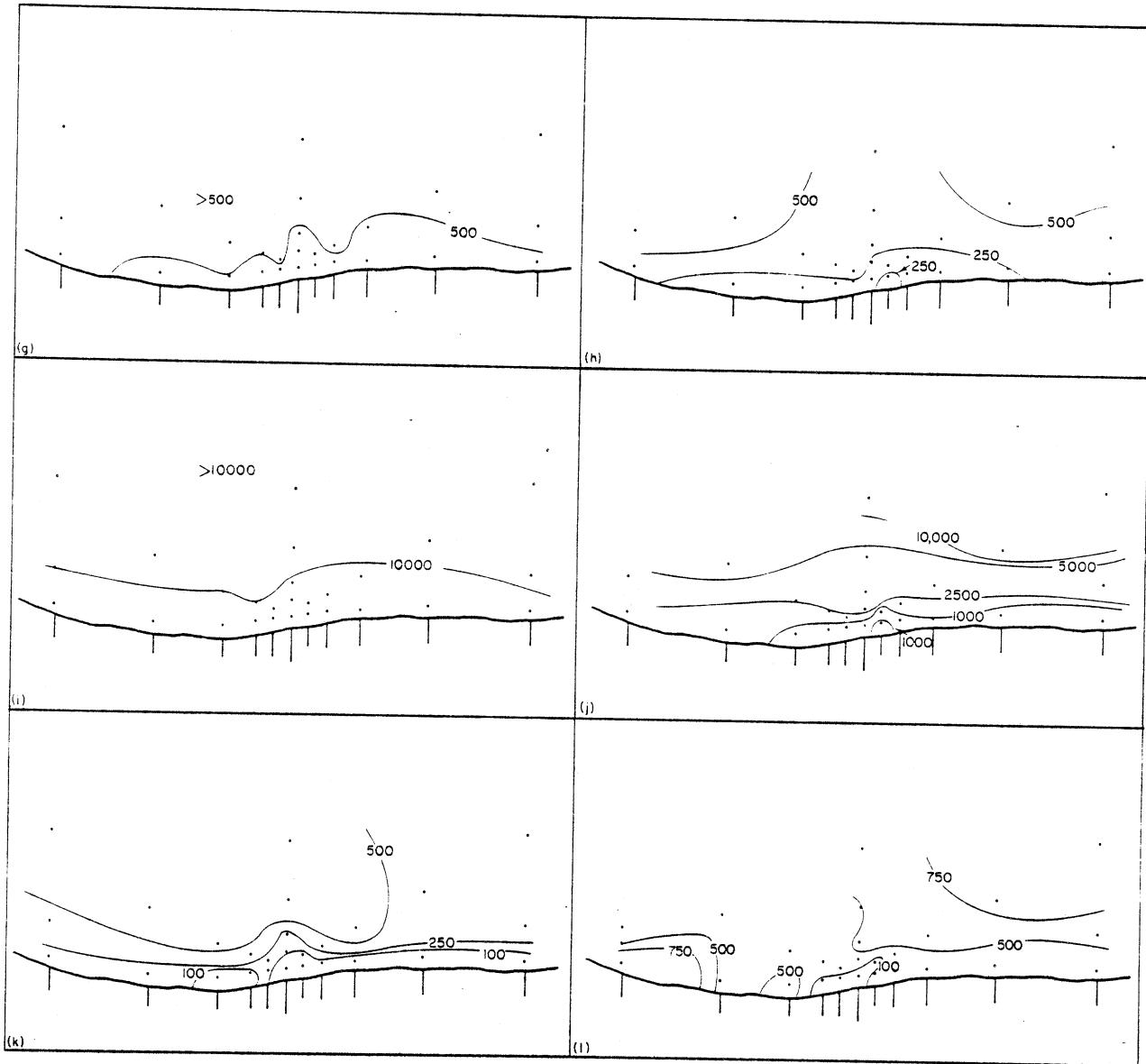


FIG. 17 continued. g,h) Cyclops spp. C6, i,j) Diaptomus spp. C1-C5, k,l) Diaptomus spp. C6.

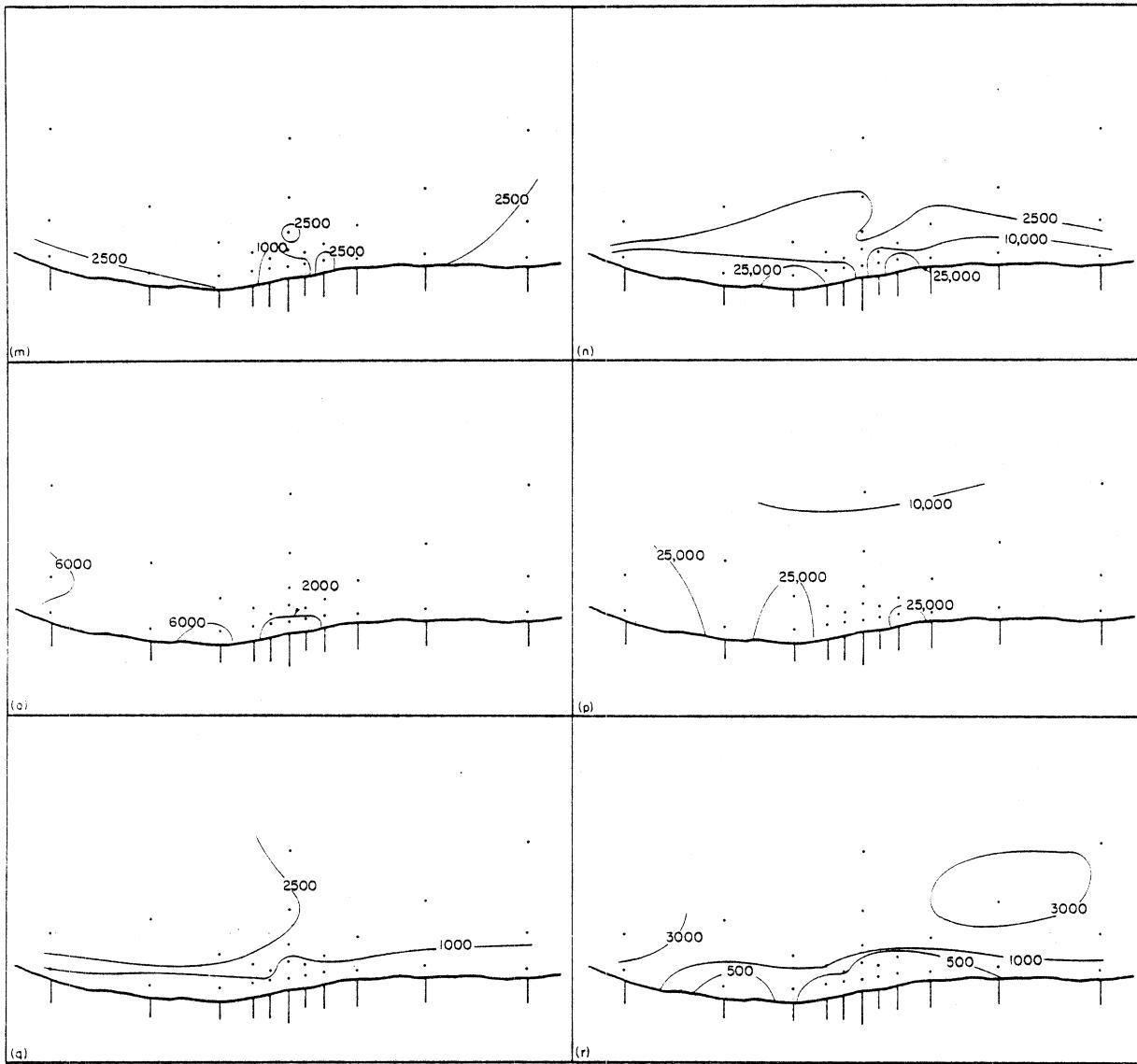


FIG. 17 continued. m,n) Bosmina longirostris, o,p) Eubosmina coregoni and q,r) Daphnia spp.

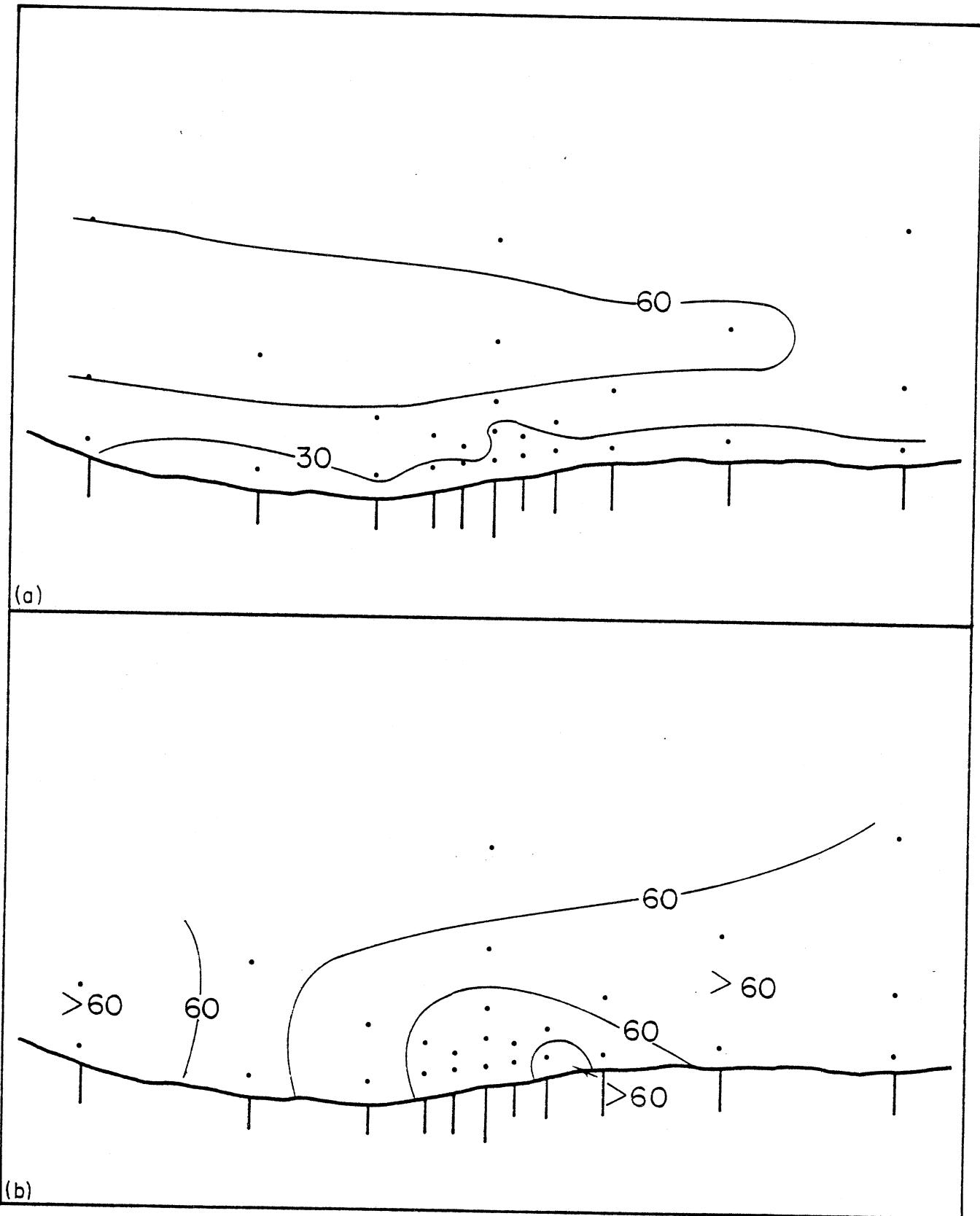


FIG. 18. The standing stock of zooplankton (mg dry weight/m³) on a) 17 October 1975, b) 14 October 1976.

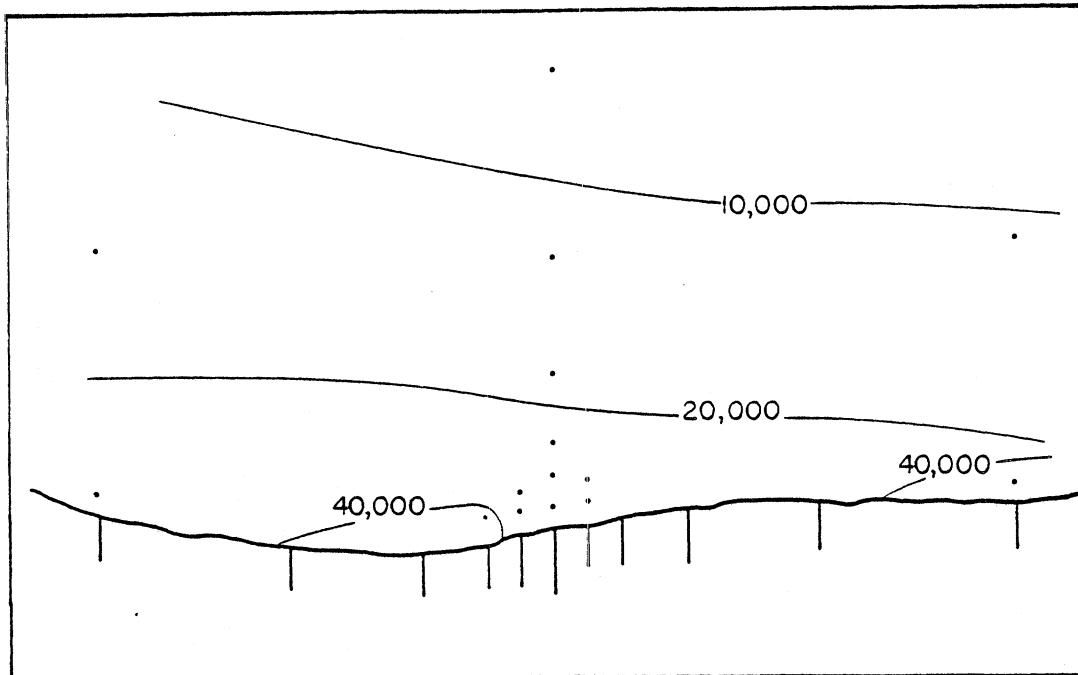


FIG. 19. The horizontal distribution of total zooplankton (number/m³) collected on 5 December 1975.

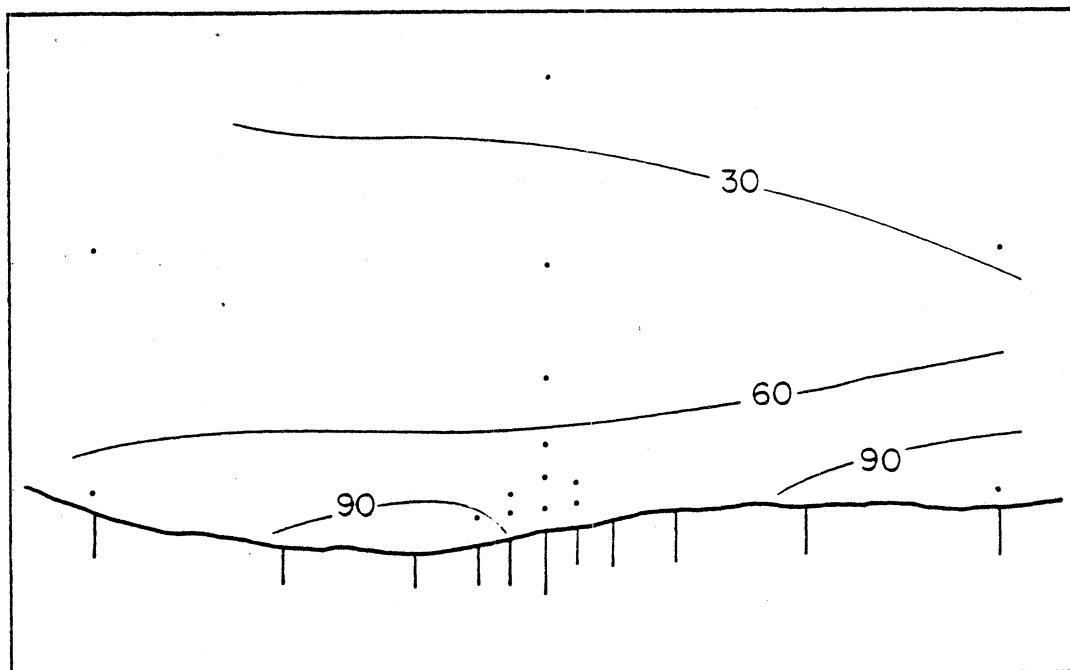


FIG. 20. The standing stock of zooplankton (mg dry weight/m³) on 5 December 1975.

TABLE 4. The percentage of variance explained by PC1 and PC2 in analyses of major survey samples.

PC	April		July		October		December
	1975	1976	1975	1976	1975	1976	1975
PC 1	54.1	60.2	83.5	72.7	66.2	64.5	91.7
PC 2	21.3	15.4	7.8	10.0	14.5	12.6	4.8

April

Analyses of the operational (1975, 1976) and preoperational (1972, 1973, 1974) April data sets gave less consistent results than the analyses of the July and October data. These inconsistencies appeared to be related to lake temperatures over the entire survey grid at the time of the cruise. Generally, the results of the April analyses were most similar to the results of the July and October analyses when lake water temperatures were greater than 4°C over the entire survey grid.

While in 1973 and 1974, ordination of stations by their first and second principal component values revealed the three depth-related groups of stations, these groups were less distinct in 1972, 1975, and 1976. In 1975, a cruise similar to the April 1972 cruise where lake temperatures ranged from 2 to 6°C , there was some separation of the offshore groups of stations while the inshore and middle stations formed a mixed group (Fig. 21a). PC1 was negatively correlated with station depth and Secchi disc depth and positively correlated with temperature (Table 5). Ordination of the April 1976 data (Fig. 21b) resulted in the separation of the inshore and middle stations along the PC1 axis while the offshore group divided into two clusters. The group with high PC2 values included stations in warmer ($>4^{\circ}\text{C}$), shallower (<30 m) waters than the second group with lower PC2 values. PC1 in April 1976, as in the relatively warm April 1973 and 1974, was positively correlated with station depth and Secchi disc depth and negatively correlated with temperature (Table 5).

The numerically dominant taxa in April 1975 and 1976 were *Cyclops* spp. and *Diaptomus* spp. copepodites and their nauplii. *Limnocalanus macrurus*, a third copepod genus, was of lesser numerical importance. Copepodite concentrations were positively correlated with PC1 in both years (L. *macrurus* correlations were negative in 1975) although the correlations were higher in 1976 (Table 5). As would be expected (since PC1 was correlated with station depth) the abundance of these taxa over the survey grid was related to

TABLE 5. Correlations (r) between zooplankton ($\log \#/m^3 + 1$) taxa used in the analyses, station depth, Secchi disc depth, surface water temperatures and the first principal component.

Taxon	April 1975	1976	July 1975	1976	October 1975	1976	December 1976
Copepod nauplii	0.74	0.37	0.85	-0.24	0.67	0.26	-0.85
Cyclopoid copepods C1-C5	0.35	0.87	0.96	0.79	0.90	0.93	0.79
<u>Cyclops</u> spp. C6	0.39	0.88	0.97	0.98	0.82	0.87	0.94
<u>Tropocyclops prasinus</u> m. C1-C6	----	----	0.13	-0.75	0.85	0.84	0.91
<u>Diaptomus</u> spp. C1-C5	0.70	0.68	0.97	0.77	0.97	0.92	0.77
<u>Diaptomus</u> spp. C6	0.46	0.85	0.88	0.64	0.92	0.80	0.88
<u>Epischura lacustris</u> C1-C6	----	----	----	----	-0.15	0.53	----
<u>Eurytemora affinis</u> C1-C6	----	----	-0.50	-0.78	-0.83	-0.01	----
<u>Limnocalanus macrurus</u> C1-C6	-0.13	0.92	----	----	----	----	----
<u>Bosmina longirostris</u>	0.97	0.13	0.88	-0.81	-0.06	-0.87	0.98
<u>Daphnia</u> spp.	----	----	0.96	0.88	0.91	0.94	0.98
<u>Eubosmina coregoni</u>	----	----	0.94	0.27	0.48	-0.29	0.99
Minor cladocerans	----	----	-0.39	-0.12	0.30	-0.68	----
<u>Asplanchna</u> spp.	----	----	-0.51	-0.59	0.55	-0.83	----
Station Depth	-0.59	0.59	0.82	0.82	0.87	0.86	-0.94
Water Temperature	0.34	-0.40	-0.62	-0.52	-0.08	-0.25	-0.56
Secchi disc depth	-0.29	0.33	0.83	-0.07	0.86	0.72	-0.89

---- Taxa not included in the analysis.

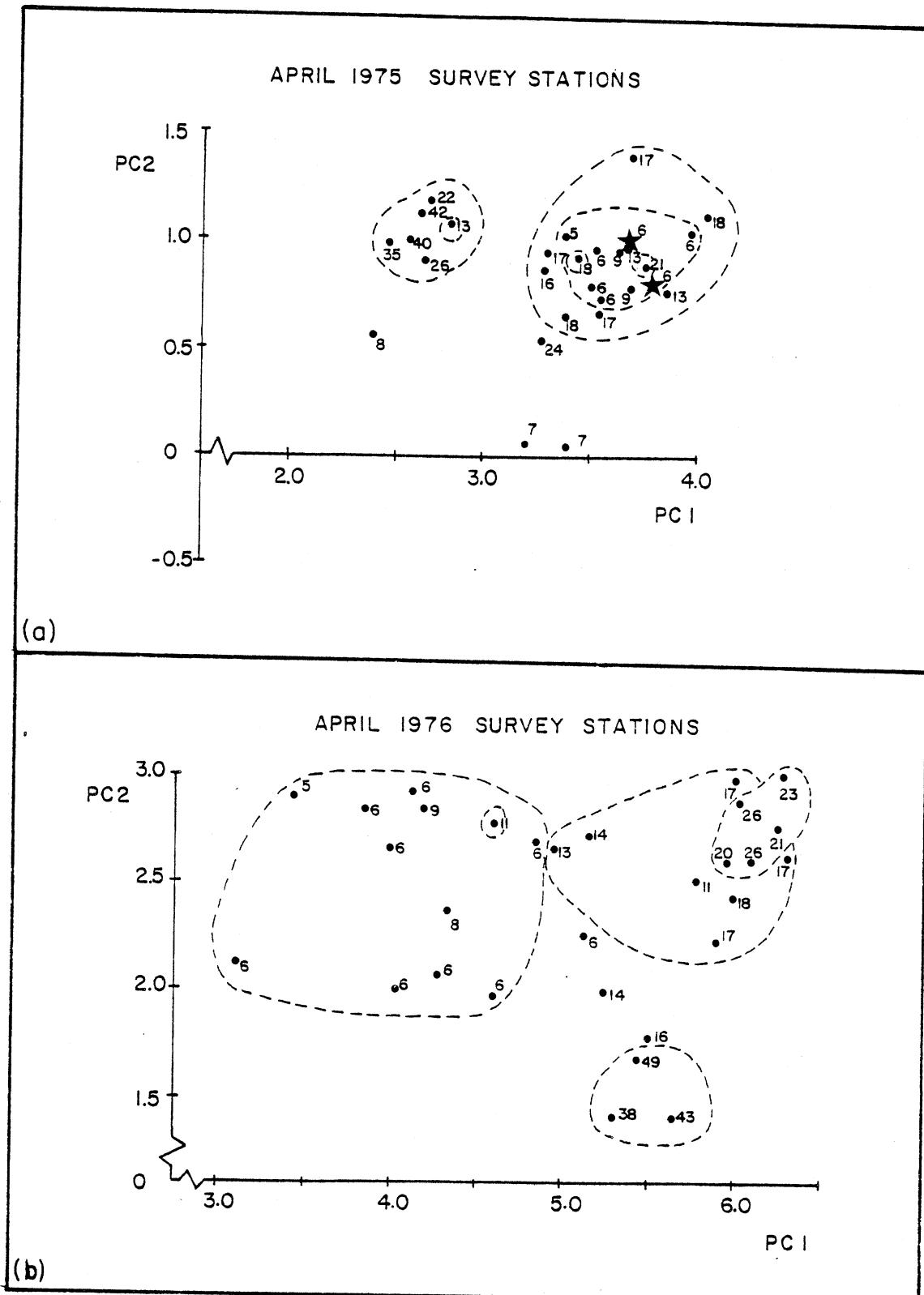


FIG. 21. Principal component ordination of survey stations sampled on a) 17 April 1975, b) 14 April 1976. Station depth (m) is noted next to each point. Dotted lines roughly separate stations of three depth intervals: 5-10 m, 10-20 m and 20-50 m. ★ indicates stations in the thermal plume.

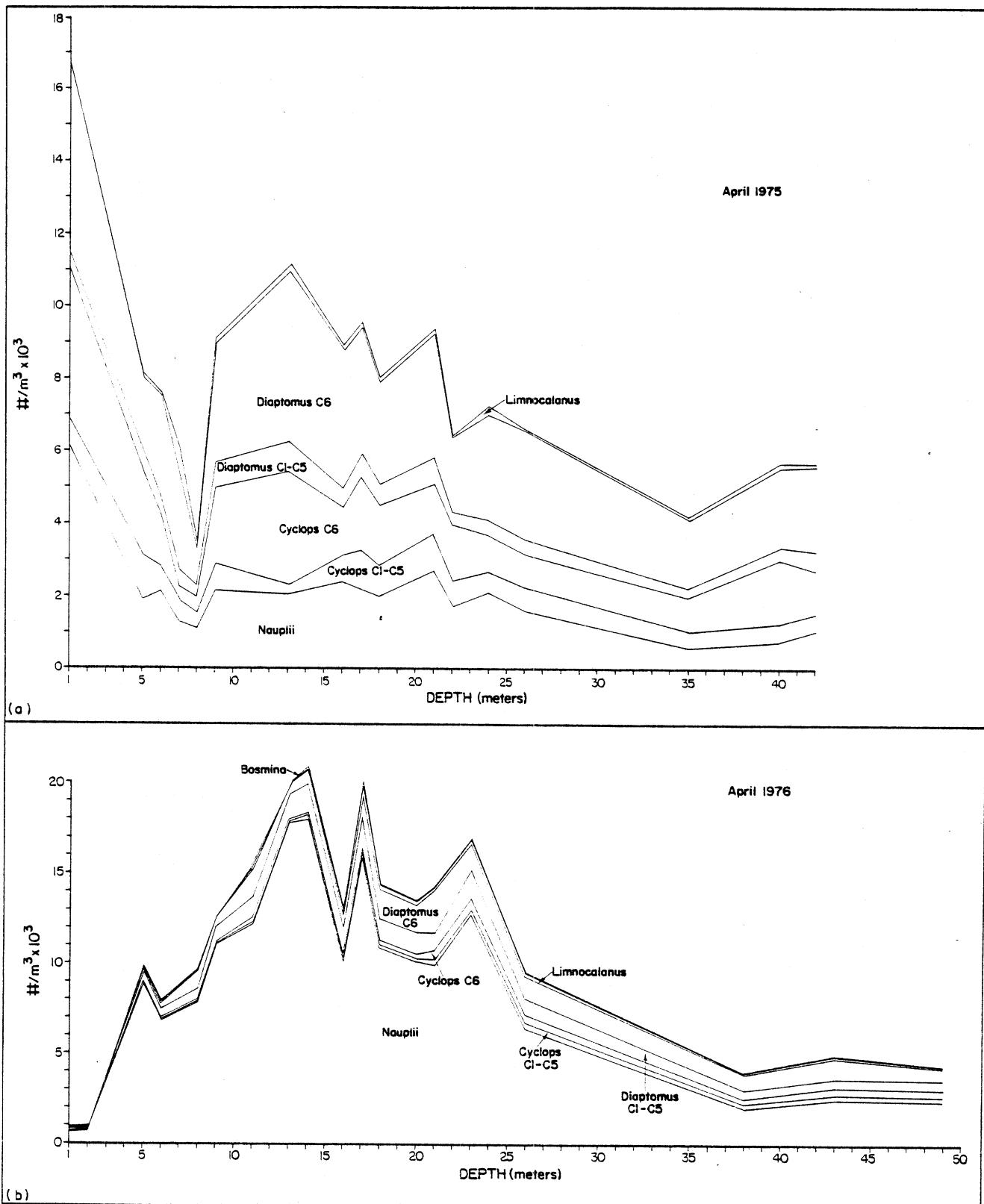


FIG. 22. Zooplankton abundance versus station depth. a) 17 April 1975, b) 14 April 1976.

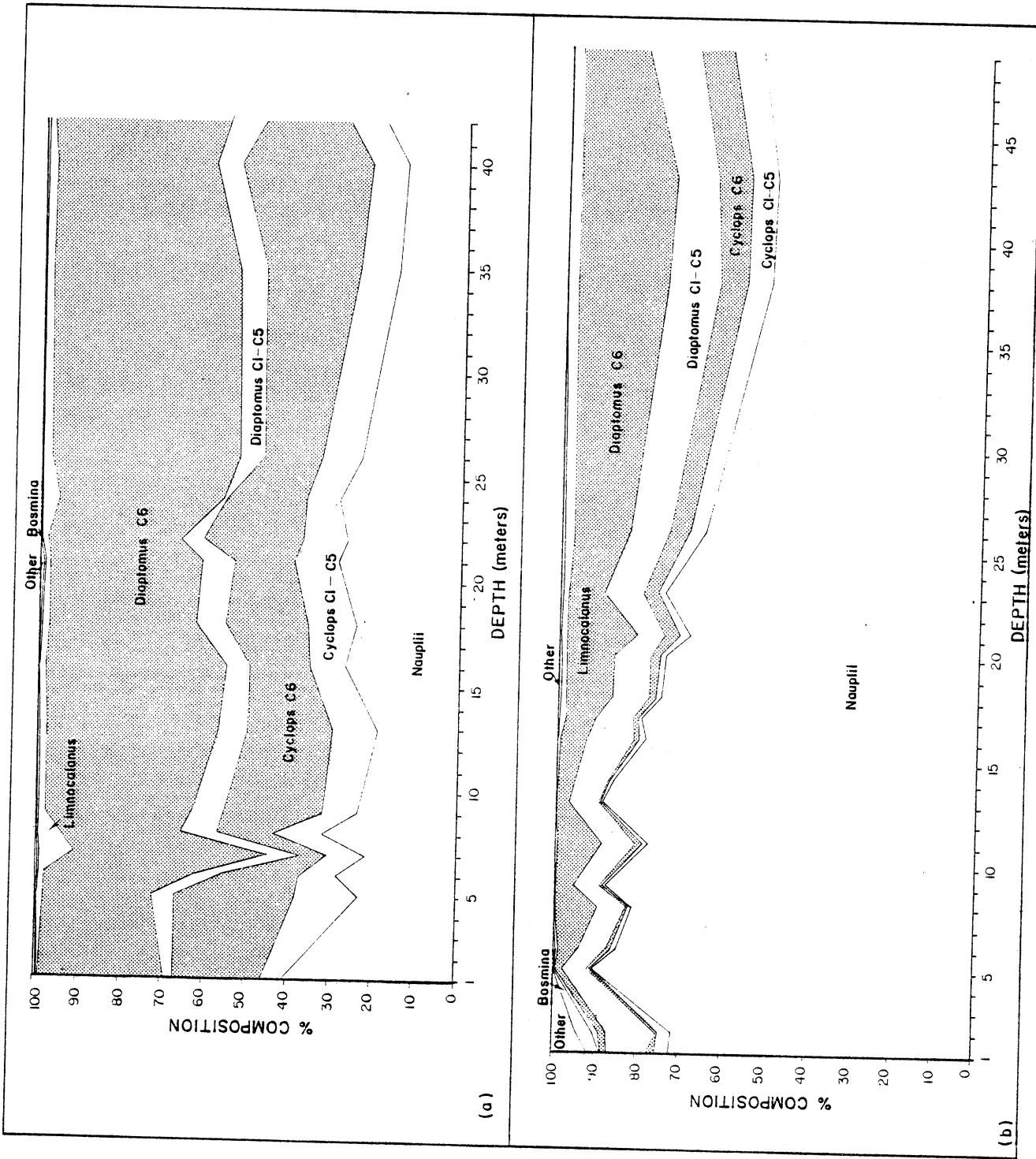


FIG. 23. Zooplankton composition versus station depth. a) 17 April 1975, b) 14 April 1976.

depth. In April 1975, these taxa tended to occur in their highest concentrations in the shallower waters of the survey grid. In April 1976, copepodites occurred in low concentrations in the inshore region and in increasing concentrations with increasing water depth (Fig 22); however, the area of maximum concentration did not occur at the deepest stations. Increases in zooplankton concentrations with water depth were not as great as in 1973 (Stewart 1974) or 1974 (Evans and Hawkins 1975). The percent composition of zooplankton changed with increasing water depth with adult Cyclops spp. and Diaptomus spp. accounting for an increasingly large fraction of the zooplankton with depth in April 1976 (Fig. 23). A similar trend was exhibited by the immature copepodites of these genera and by Limnocalanus macrurus. In April 1975, Cyclops spp., Diaptomus spp., and L. macrurus occurred in similar percent compositions over most of the inshore-middle-offshore region.

In April 1975, zooplankton concentrations were high in the beach region (1 to 2-m of water) with nauplii and adult Cyclops spp. and Diaptomus spp. particularly abundant (Fig 22). In April 1976, zooplankton were rare in this region. Inclusion of the beach stations into the April 1975 and 1976 survey cruise analyses did not alter the basic relationship (Fig. 24) between the 30 lake stations. However, the beach stations formed a group which was distinct from the inshore-middle-offshore complex and was not a continuum of the inshore region.

There was no evidence from the principal component analyses (Fig. 24) that stations located in the thermal plume had zooplankton population structures which were different from those at stations located upcurrent and downcurrent of the plume. Stations in the plume had similar PC1 and PC2 values as stations located in comparable depths of water and outside the plume.

July

The results of the July analyses were more consistent from year to year than were the results of the April analyses. Principal component ordination of the July 1975 and 1976 lake data (Fig. 25) produced a semi-circular pattern of stations which generally increased in depth along the PC1 axis. The first principal component was positively correlated with depth and negatively correlated with temperature in both years (Table 5). The correlation with Secchi disc depth was positive in 1975 and slightly negative in 1976. Similar results were obtained with the 1972, 1973, and 1974 analyses.

Cyclops spp., Diaptomus spp., and Daphnia spp. concentrations were positively correlated with PC1 (Table 5). As would be expected, these taxa occurred in their lowest concentrations in the inshore region and increased sharply in concentration out to the 20 or 30-m depth contour. In deeper waters, concentrations remained the same or decreased slightly (Fig. 26).

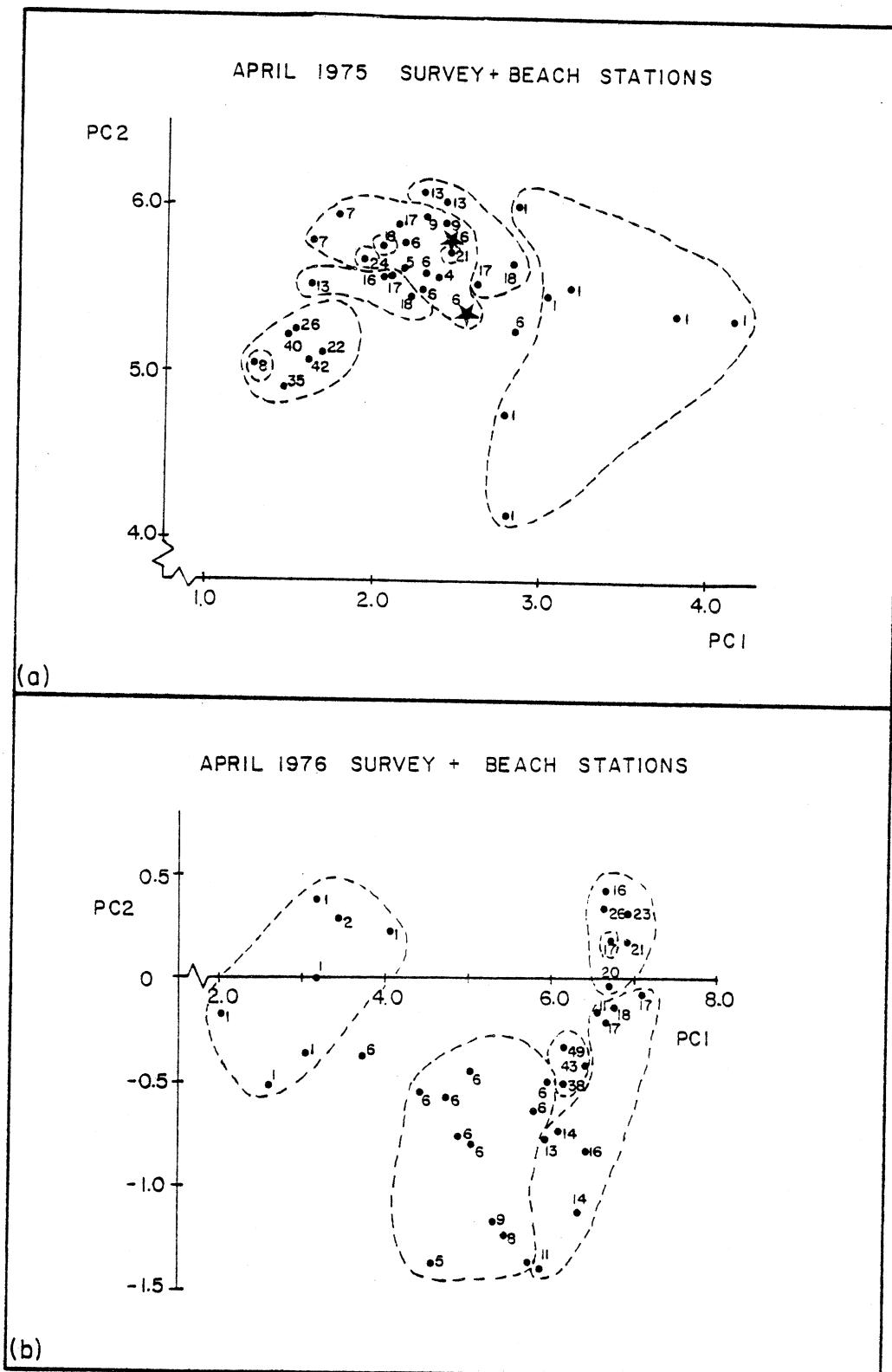


FIG. 24. Principal component ordination of survey and beach stations sampled on a) 17 April 1975, b) 14 April 1976. Dotted lines separate stations of four depth intervals: 1-2 m (beach), 2-10 m, 10-20 m and 20-50 m. ★ indicates stations in the thermal plume.

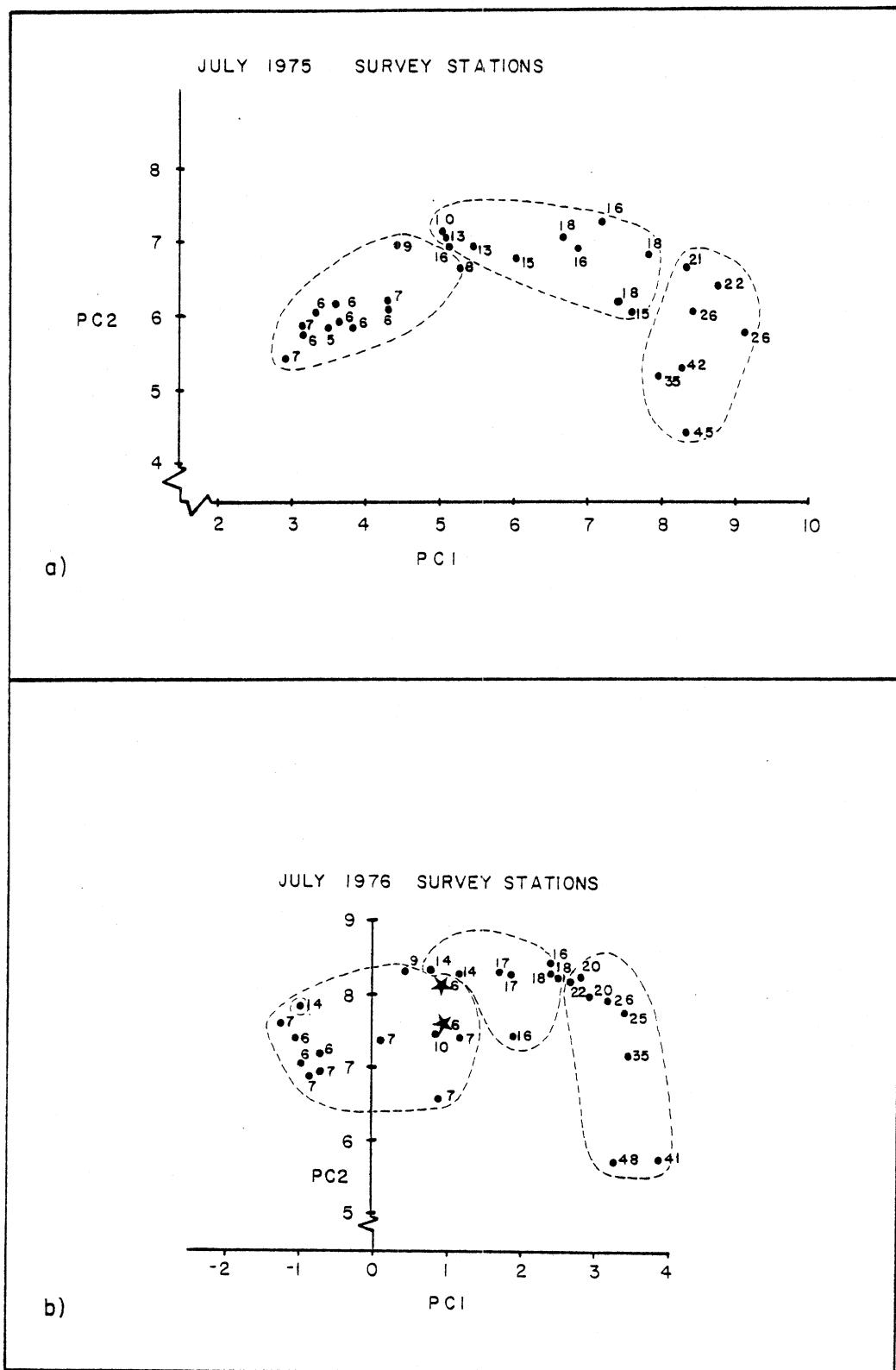


FIG. 25. Principal component ordination of the survey stations sampled on a) 17 July 1975, b) 15 July 1976. ★ indicates stations in the thermal plume.

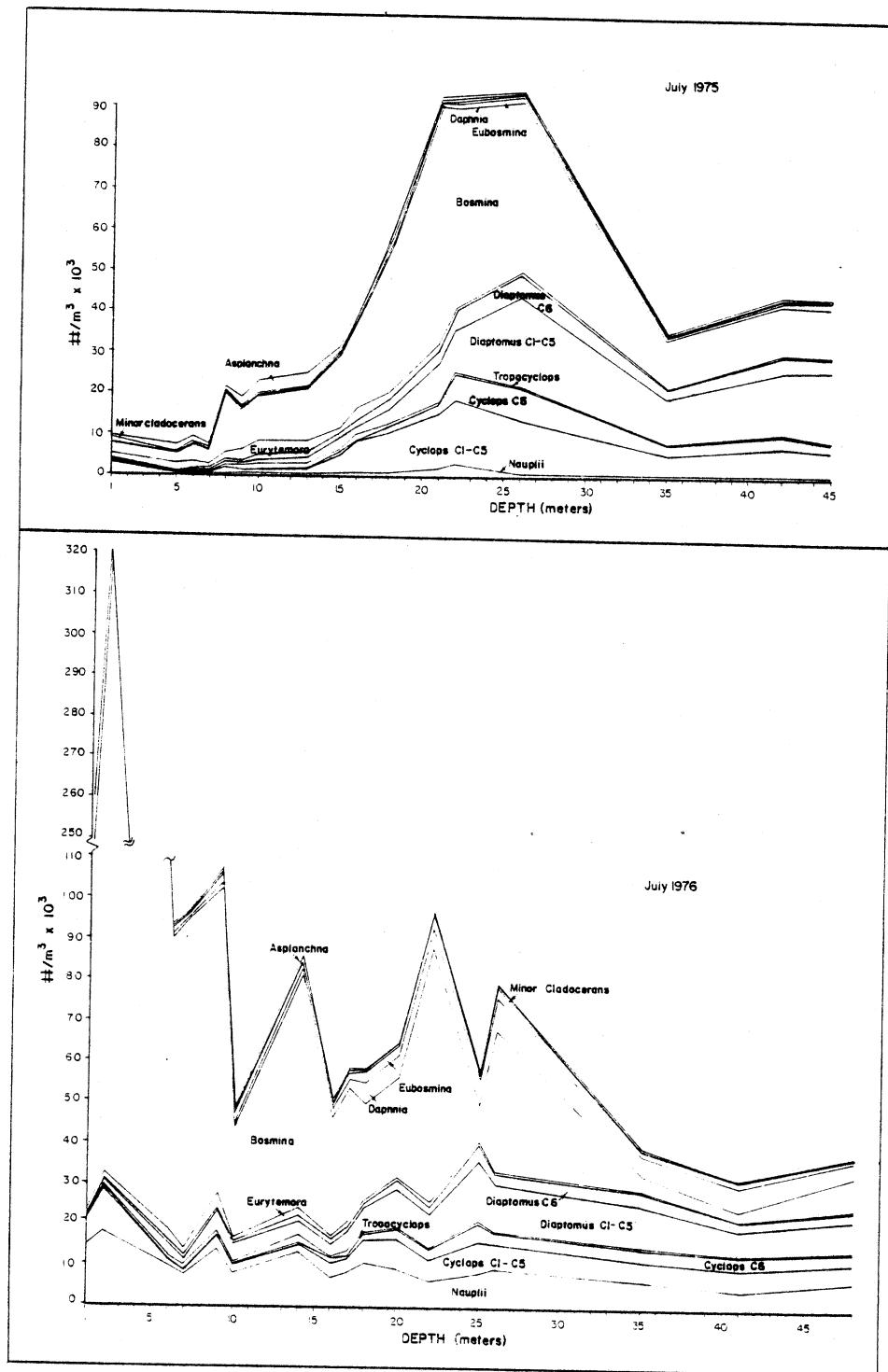


FIG. 26. Zooplankton abundance versus station depth. a) 17 July 1975, b) 15 July 1976.

The area of maximum zooplankton concentration did not correspond to any common isotherm or Secchi disc depth between the two years. Rather, the area of maximum concentration occurred in approximately the same area of the lake in all years despite considerable variations in Secchi disc depth. Thus, its location would appear to be somewhat independent of phytoplankton standing stocks. Cyclops spp., Diaptomus spp., and Daphnia accounted for an increasingly large proportion of the zooplankton with increasing water depth (Fig. 27). This was also observed in the preoperational period.

Bosmina longirostris, Eubosmina coregoni, and nauplii occurred in increasing concentrations with increasing water depth out to the 20 or 30-m depth contour in July 1975 (Fig. 26) and in the preoperational years. However, in July 1976, these taxa were negatively correlated with PC1 and tended to occur in lower concentrations with deeper waters. In both July 1975 and 1976, Asplanchna spp. and the copepod Eurytemora affinis were negatively correlated with PC1 and occurred in maximum concentrations in the shallowest waters of the survey grid.

In both July 1975 and 1976, copepod concentrations in the beach region were similar to or slightly higher than concentrations in the inshore region. Nauplii and immature Cyclops spp. and Eurytemora affinis were the numerically dominant copepods (Fig. 26). Bosmina longirostris was the numerically important cladoceran and was particularly abundant in the beach region in 1976. When the July 1975 and 1976 principal component analyses were performed with the inclusion of the beach stations, the essential relationship between the inshore, middle, and offshore stations remained the same (Fig. 28) and again the beach stations formed a distinct group.

There was no evidence from the principal component analyses of the July 1976 data that zooplankton population structure was different in the thermal plume than at stations upcurrent and downcurrent of the discharge jets. The two stations located in the plume had PC1 and PC2 values (Fig. 28) similar to those for the other inshore stations. The plant was not operational during the July 1975 cruise.

October

In October 1975 and 1976, PC1 accounted for approximately 65% of the total variance (Table 4) and was positively correlated with station depth (Table 5). Correlations with Secchi disc depth were also positive but lower in magnitude while correlations with temperature were negative. Principal component ordination revealed the same depth-related groupings of stations (Fig. 29) although the groups were not as distinct as in July. In both October cruises, only three or four of the seven offshore stations were sampled. Similar results were obtained with the analyses of the October preoperational (1972, 1973, 1974) data.

Cyclops spp., Diaptomus spp., and Daphnia spp. abundances were

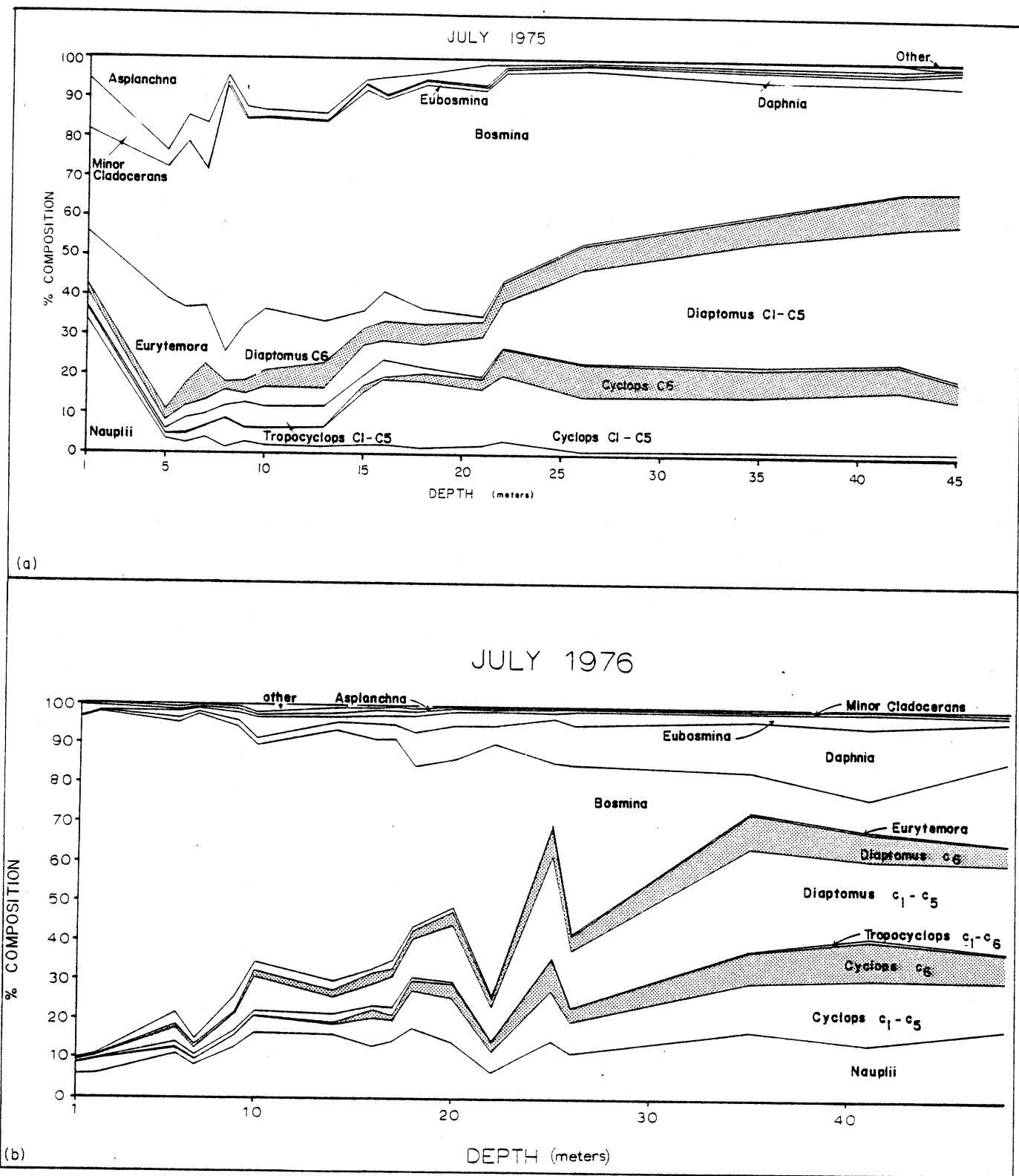


FIG. 27. Zooplankton composition versus station depth. a) 17 July 1975, b) 15 July 1976.

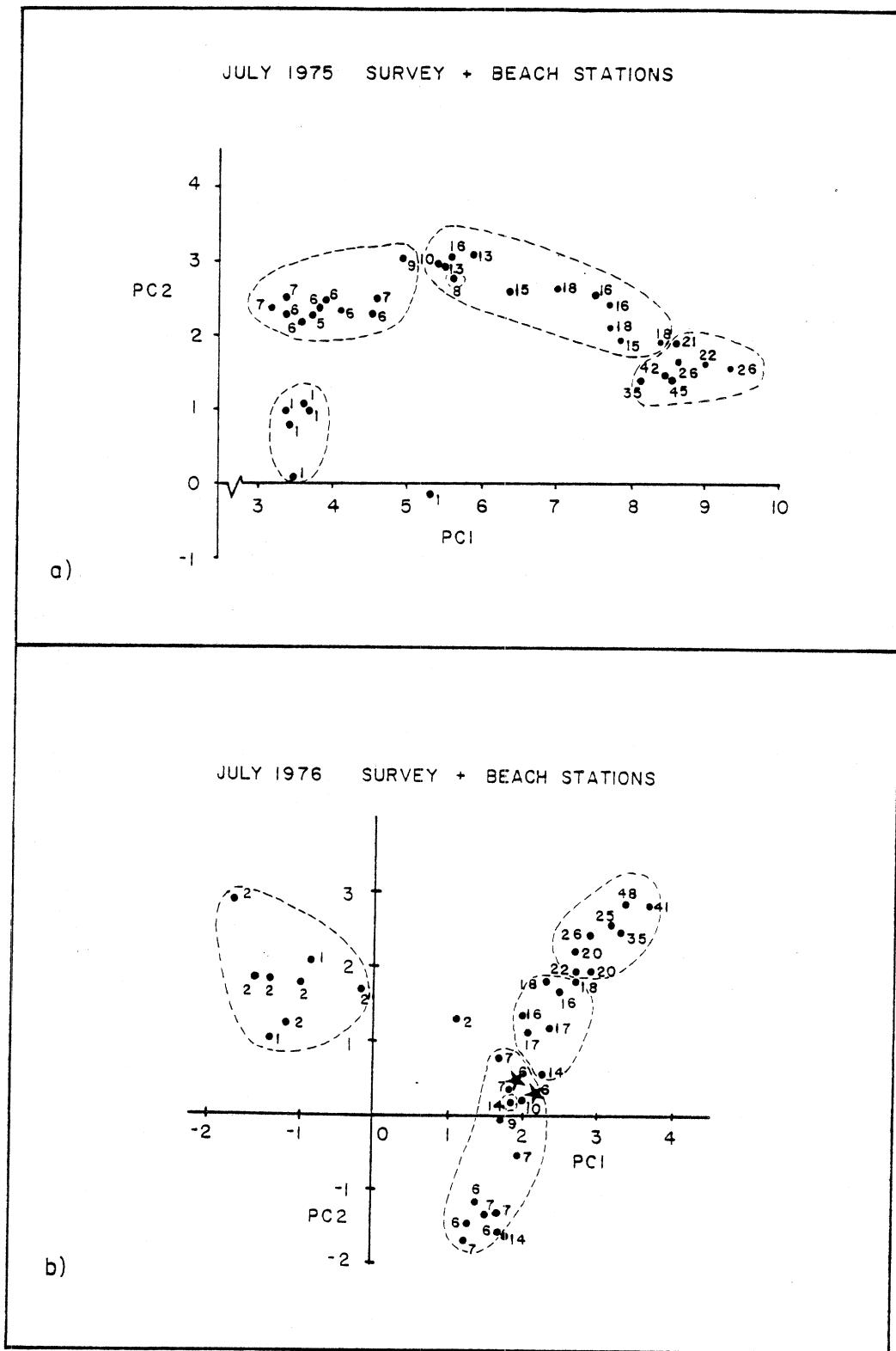


FIG. 28. Principal component ordination of the survey and beach stations sampled on a) 17 July 1975, b) 15 July 1976. ★ indicates stations in the thermal plume.

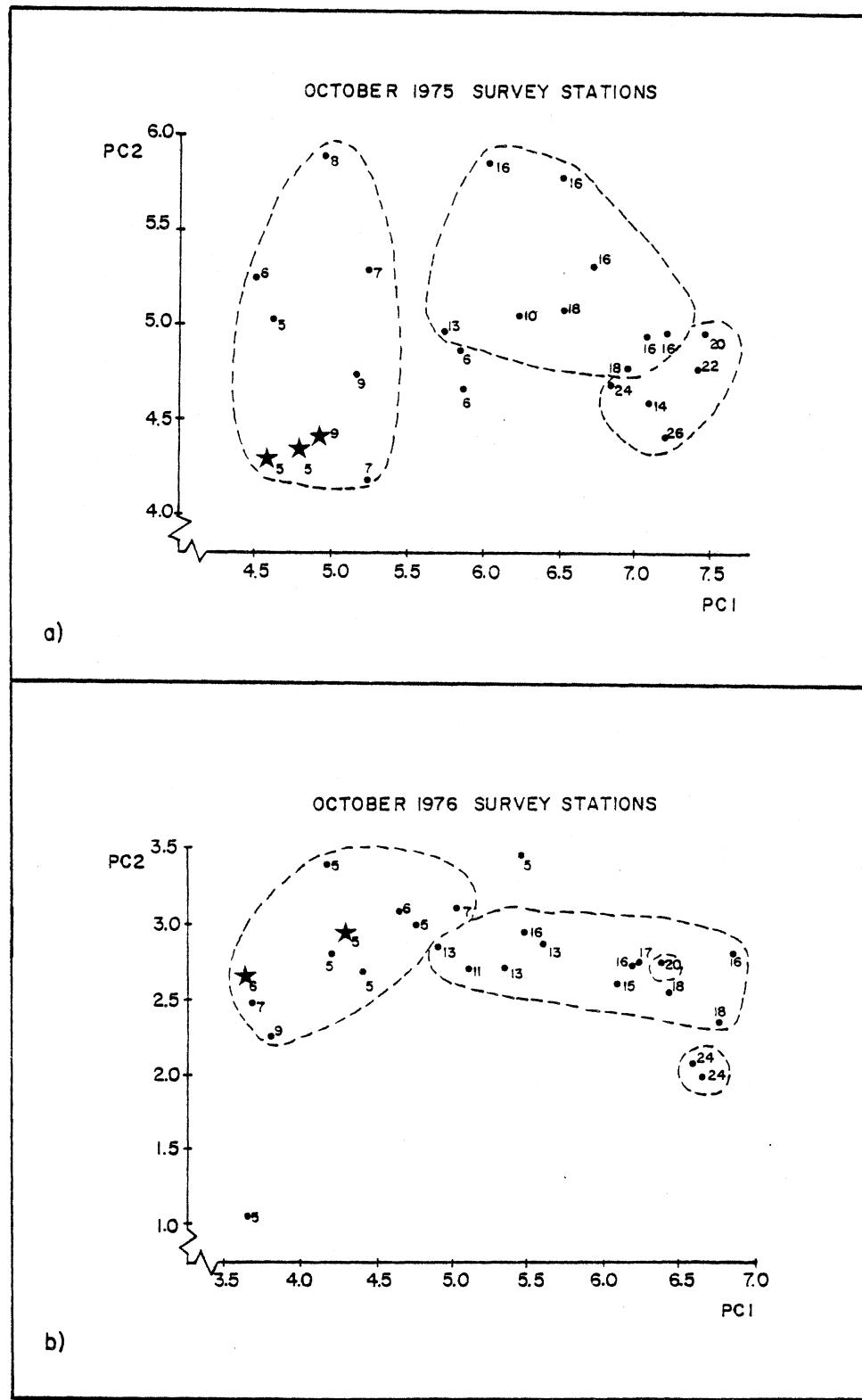


FIG. 29. Principal component ordination of the survey stations sampled on a) 17 October 1975, b) 14 October 1976. ★ indicates stations in the thermal plume.

positively correlated with PC1. As in July, these taxa increased in abundance with increasing water depth (Fig. 30) out to the 25 m depth contour. Zooplankton populations were not sampled beyond this depth in 1975 and 1976 and so it is not known whether zooplankton decreased in concentrations beyond the 25-m depth contour. These taxa accounted for an increasingly large fraction of the zooplankton population (Fig. 31) with increasing water depth in 1976, but in October 1975 the differences in zooplankton abundance and composition across the survey grid were not as great. Correlations of Bosmina longirostris and Eubosmina coregoni with PC1 were low or negative.

In 1975, zooplankton populations were slightly higher in the beach region than in the inshore region and immature Cyclops spp. and nauplii were the dominant forms (Fig. 31). Inclusion of the beach stations in the October 1975 principal component analysis did not result in an alteration of the basic relationship between the inshore-middle-offshore complex of stations (Fig. 32). The beach stations formed a group which was distinct from this complex rather than a continuum of the inshore region.

Three stations in October 1975 and two stations in October 1976 were located in the thermal plume. These stations had PC1 and PC2 values (Fig. 29, 32) similar to those of stations located outside the plume and in comparable depths of water. This indicates that zooplankton population structure was not grossly altered within the thermal plume.

December

Only one December cruise (1975) has been taken during the several years of the cruise program. The results of the December analysis differed from the previously described April, July, and October analyses. The first principal component was negatively correlated with station depth and with Secchi disc depth (Table 5) as in the cold April 1975 cruise. However, in December PC1 was negatively correlated with temperature while in April 1975 the correlation was positive. Principal component ordination of the December data produced a depth-related grouping of stations where station depth decreased along the PC1 axis (Fig. 33). Unlike the results of the April 1975 analysis, the December analysis produced a distinct grouping of stations. The December grouping of stations along the PC1 axis was the reverse of the July analyses indicating that between the October and December cruises, the basic relationship between zooplankton abundance and station depth reversed.

Apart from nauplii, all taxa had high, positive correlations with PC1 (Table 5). All taxa showed a trend of decreasing concentrations (Fig. 34a) with increasing water depth. This pattern was similar to the April 1975 analysis. In both months, the percent composition of zooplankton was similar at all station depths (Fig. 34b).

Two stations were located in the thermal plume during the December

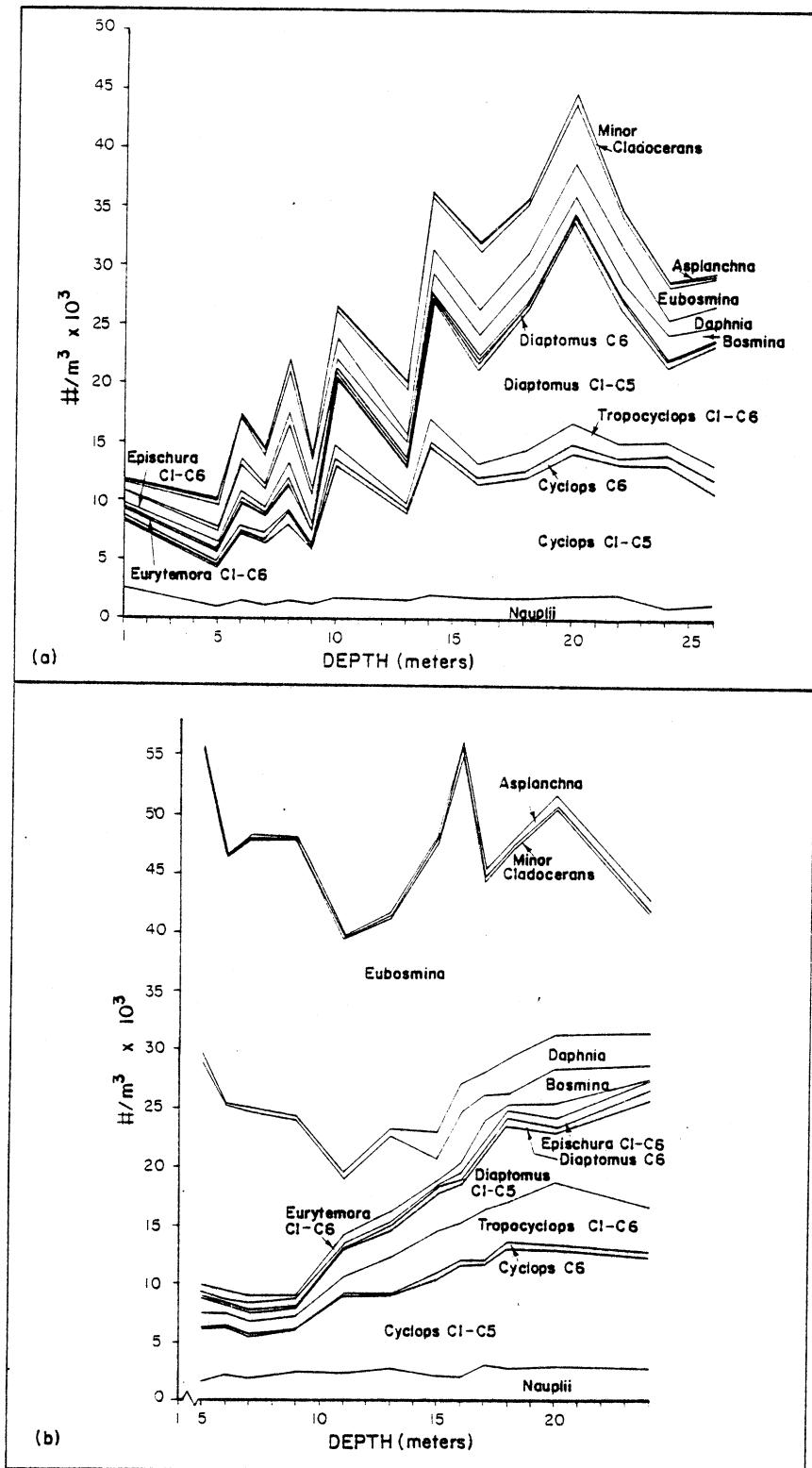


FIG. 30. Zooplankton abundance versus station depth. a) 17 October 1975, b) 14 October 1976.

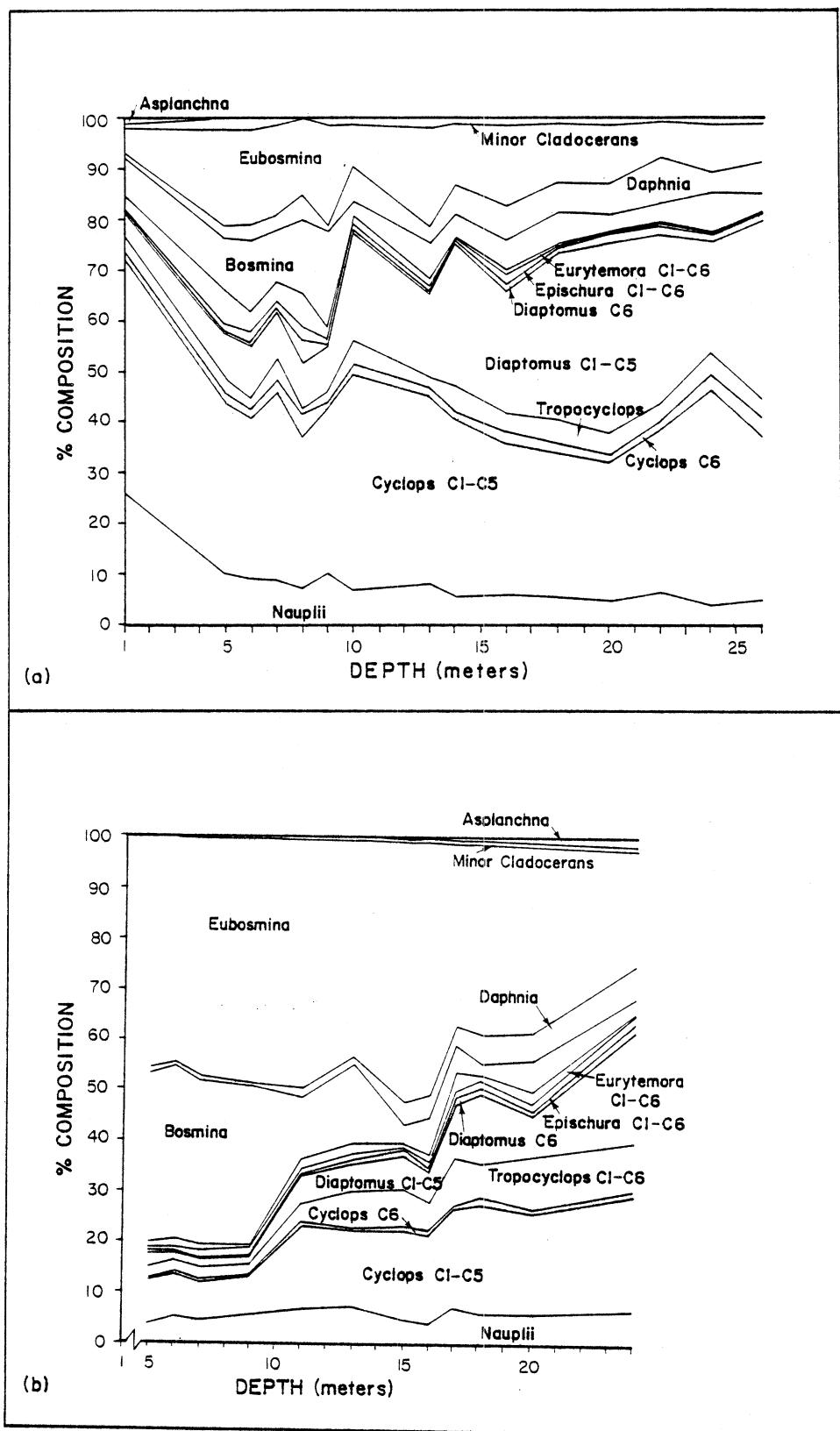


FIG. 31. Zooplankton composition versus station depth.
 a) 17 October 1975, b) 14 October 1976.

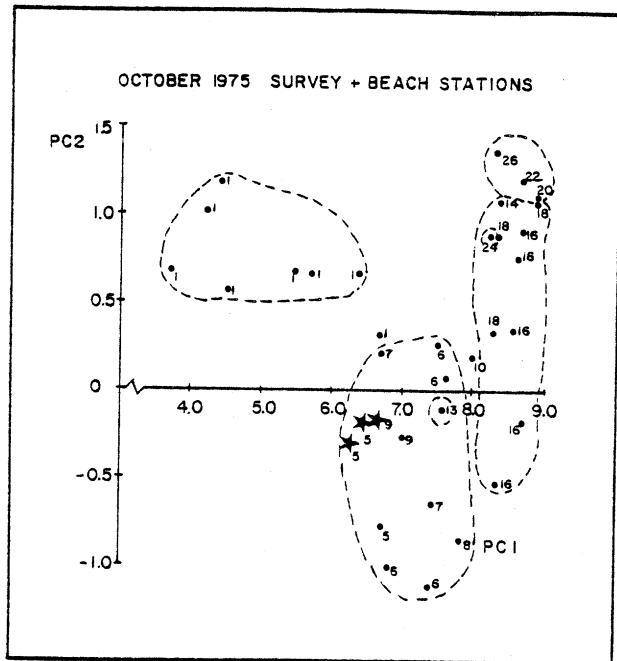


FIG. 32. Principal component ordination of the survey and beach stations sampled on 17 October 1975. \star indicates stations in the thermal plume.

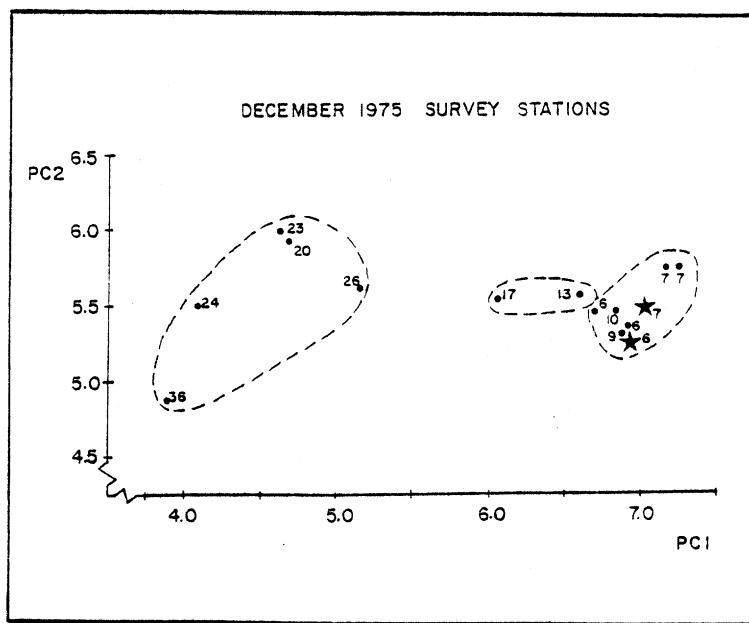


FIG. 33. Principal component ordination of the survey stations sampled on 5 December 1975. \star indicates stations in the thermal plume.

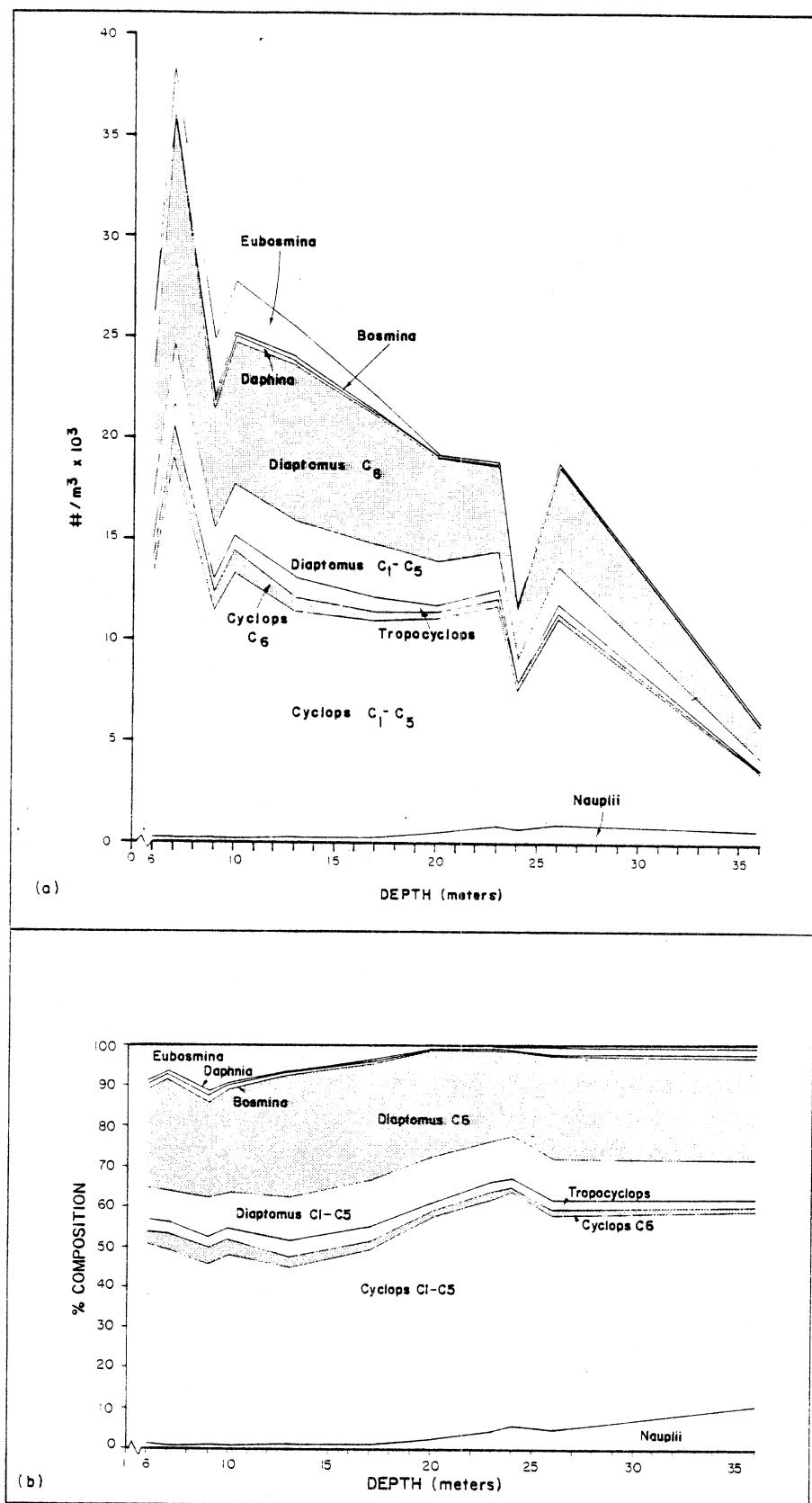


FIG. 34. Zooplankton abundance a) and composition b) versus station depth on 5 December 1975.

cruise. These stations had PC1 and PC2 values similar to those of stations located outside the plume and in comparable depths of water (Fig. 33). This indicates that zooplankton population structure was not grossly altered within the thermal plume.

DISCUSSION AND SUMMARY

Cruises conducted in 1975 and 1976 provided information on the effects of power plant operation on zooplankton populations in southeastern Lake Michigan. Although the power plant utilized tremendous volumes of water and heated it over 10°C above ambient temperatures, the thermal plume ($\Delta T 0.5^{\circ}\text{C}$) was relatively small ($<3\text{ km}^2$). At DC-1, located within meters of the discharge jets, plume water was only 2 or 3°C above ambient temperatures and the plume approached ambient temperatures within 1 or 2 km of the discharge site. This cooling of heated water was accomplished by mixing with lake water, with the most rapid mixing occurring in the vicinity of the discharge jets. The power plant, by utilizing subsurface discharge jets, minimized heat stress experienced by plume-entrained zooplankton. Condenser-passed zooplankton were exposed to water 11.7°C above ambient temperature for three minutes while these zooplankton and plume entrained zooplankton experienced a ΔT of 5.6°C for one minute, a ΔT of 2.8°C for 16 minutes, and a ΔT of 1.7°C for approximately 125 minutes (United States Atomic Energy Commission 1973).

Zooplankton abundance patterns over the survey grid in 1975 and 1976 were similar to those in the preoperational years. There was no evidence that zooplankton populations were grossly altered in the thermal plume either at the genus or species level (abundance plots) or at the community level (principal component analysis).

The zooplankton community continued to show a depth-related pattern of abundance with Cyclops spp., Diaptomus spp., Daphnia spp., and Limnocalanus macrurus exhibiting the most pronounced and consistent patterns. The several years of preoperational and operational data have revealed the major features of this pattern. The seasonal pattern is hypothesized to have occurred as described in the following paragraphs.

In the early spring before the thermal bar migrated offshore, zooplankton abundances tended to be negatively correlated with depth, with maximum copepod concentrations occurring close to shore. With lake warming, the pattern reversed and by the time lake temperatures exceeded 4°C over the entire survey grid, zooplankton occurred in the lowest concentrations close to shore. This reversal in the zooplankton abundance-depth gradient developed as Cyclops spp., Diaptomus spp., and Limnocalanus macrurus became less abundant in the inshore region rather than by their numbers increasing offshore. The depth-related pattern in Cyclops spp., Diaptomus spp. and in Daphnia spp. distributions continued through the summer with these taxa increasing markedly in abundance between the 5 and 20-m depth contours and

then leveling off or decreasing slightly. In the summer, L. macrurus was rare over the survey grid with maximum concentrations occurring beyond the 30-m depth contour. Some cladocerans such as Bosmina longirostris and Eubosmina coregoni also increased in abundance with distance offshore although this gradient was not as steep as the Cyclops spp., Diaptomus spp., and Daphnia spp. gradients and the trend was not as consistent from year to year. The Cyclops spp., Diaptomus spp., and Daphnia spp. distribution pattern continued through the autumn and became less pronounced. By December the pattern reversed, and Cyclops spp. and Diaptomus spp. occurred in maximum concentrations close to shore and in decreasing concentrations with distance offshore. The December pattern was similar to the pattern observed in a cold April such as 1975 and was also observed in western Lake Michigan by Beeton and Barker (1974).

Zooplankton also varied in composition with water depth. During the early spring, the late autumn, and December, zooplankton compositions were similar at all depths of the survey grid. However, from the mid-spring to mid-autumn, there were pronounced differences in zooplankton composition with station depth. Cyclops spp., Diaptomus spp., Daphnia spp., and Limnocalanus macrurus all tended to account for increasingly large fractions of the zooplankton with increasing water depth while smaller-bodied forms such as Bosmina longirostris, nauplii, and Asplanchna spp. accounted for decreasing fractions of the zooplankton.

The nearshore area is extremely complex and many factors probably influenced the seasonal depth-related patterns of zooplankton abundance. We hypothesize that three factors were of prime importance in determining the spatial patterns. These are size-selective fish predation, lake temperatures, and phytoplankton standing stock.

In the early spring, the inshore region is an area of intense lake warming and high primary production. Further offshore, lake temperatures are lower and, in the absence of thermal stratification, phytoplankton are mixed below the compensation depth. Low temperatures and the instability of the water column probably result in lower production rates in the offshore region than in the warmer, shallower inshore region. Therefore, during early spring, the inshore region is a more favorable habitat for copepod survival because of its warmer water and greater phytoplankton standing stocks. Cyclops spp., Diaptomus spp. and Limnocalanus macrurus all occurred in large numbers in this area of the lake.

With continued lake warming, production rates remain high and Cyclops spp. and Diaptomus spp. continue to reproduce. Nauplii become abundant particularly in the inshore and middle regions. At this time, there is a reduction in adult copepod numbers particularly in the inshore and middle regions. Senescent death of overwintering adults is one causal factor. However, about this time, large numbers of planktivorous fish such as the alewife, yellow perch, and smelt migrate shoreward after having overwintered

offshore in the deeper areas of the lake (Wells 1960). Alewife are size-selective obligate planktivores which can alter the zooplankton composition of a water body by their feeding behavior (Brooks and Dodson 1965, Wells 1970). Smelt (Reiff and Tappa 1966) and yellow perch (Gailbraith 1967) are facultative planktivores which also can alter zooplankton composition through their feeding behavior. Shoreward migration of large numbers of these planktivorous fish may account for the observed concentration gradients in adult Diaptomus spp., Cyclops spp., Limnocalanus macrurus and, to a lesser extent, their copepodites. Thus, while the inshore region remains favorable for zooplankton because of its warm water and large phytoplankton standing stocks, the appearance of fish planktivores produces an unfavorable habitat, particularly for the larger zooplankton.

During the summer, adult and juvenile alewife are located across the lake while larvae tend to be concentrated in the inshore region. These larvae are planktivores as are the larvae of other fish such as the spottail shiner and yellow perch. Larval fish predation on the zooplankton may produce high mortality of the larger-bodied zooplankton in the inshore region. Adult and juvenile alewife located within the 30-m depth contour also exert severe predation pressure on the zooplankton (Morsell and Norden 1968). Janssen's (1976) laboratory studies suggest that the most severe grazing pressure on the larger zooplankton should occur in the inshore region where zooplankton are least abundant (alewife exhibit pronounced size-selective feeding behavior in low concentrations of zooplankton). In addition, the shallowness of the water column in the inshore region probably provides little protection from predation for large forms such as Cyclops spp., Diaptomus spp., and Daphnia spp. Smaller zooplankton taxa such as Asplanchna spp., Bosmina longirostris, and nauplii probably are less susceptible to predation and so can occur in large numbers in the inshore region. However, in deeper waters where fish predation is less severe, these smaller zooplankton appear to be outcompeted by larger forms such as Cyclops spp., Diaptomus spp., and Daphnia spp.

Other factors in July probably account for the spatial pattern in zooplankton distributions. One of these factors is the location of the thermocline. In July, 10 m is the approximate upper limit and 20 m the approximate lower limit of the thermocline. The vertical distribution of many zooplankton taxa is related to the location of the thermocline, with taxa such as Cyclops bicuspidatus thomasi, Diaptomus ashlandi, Daphnia retrocurva, and Eubosmina coregoni spending part of the day in the metalimnion and part of the night in the epilimnion. Other taxa such as Diaptomus sicilis and Limnocalanus macrurus live primarily below the metalimnion both during the day and the night (Wells 1960; Evans unpublished data). Zooplankton which inhabit both the epilimnion and the metalimnion over the 24-hour period may receive some metabolic advantage which manifests itself in increased population size (McLaren 1974). Such species which inhabit the inshore region in the summer where colder metalimnion water is generally absent may be stressed in some way. In July, we have observed that

D. ashlandi and D. sicilis were exceedingly rare in the inshore region while D. minutus, an epilimnetic form, was abundant. The increased abundances of Diaptomus spp., L. macrurus, Cyclops spp., and Daphnia spp. with increasing water depth may be accounted for in part by the thermal structure of the water column and the physiology of these animals.

In July, zooplankton tended to occur in maximum concentrations between the 20 and 30-m depth contours and then concentrations leveled off or decreased slightly. The slight decrease was related to our sampling methods. Zooplankton occur in lower concentrations below the thermocline than above it (Wells 1960; Evans unpublished data). Since our nets sample the entire water column, samples collected from increasingly deep waters will contain decreasing numbers of zooplankton per integrated cubic meter.

In the autumn, the thermal structure of the water column and the presence of predators continues to produce a depth-related pattern in zooplankton distributions. However, with lake cooling, this pattern is reduced and then disappears. In the autumn, young-of-the-year, juvenile, and adult fish of several species migrate offshore to the deeper areas of the lake (Wells 1960; Jude et al. 1975). This migration of fish from the inshore region probably reduces predation pressure on the zooplankton, particularly the larger forms and contributes to the reduction in the zooplankton abundance-depth concentration gradient. In addition, with the loss of thermal stratification and lake cooling, the inshore and middle regions may become more favorable to those zooplankton which inhabit the metalimnion during the summer.

In the early winter, most of the planktivorous fish are beyond the survey grid overwintering in the colder, deeper portions of the lake. Phytoplankton production decreases with decreasing daylength, loss of thermal stratification of the water column, and lower temperatures. Production rates are probably highest inshore where the water column is relatively shallow and where the phytoplankton are less likely to be mixed below their compensation depth. Beeton and Barker (1974) observed that, in December, phytoplankton concentrations were highest inshore and decreased with increasing distance from shore. In December, as in April, the inshore region with its high phytoplankton concentration may be most favorable for copepod survival.

Depth-related differences in zooplankton abundance over the survey grid were generally pronounced and the nearshore area of the lake can be subdivided into several regions. Principal component ordination indicated that the inshore region occurred approximately between the 5 and 10-meter depth contours, the middle region between the 10 and 20-m depth contours, and the offshore region beyond the 20-m depth contour. However, we noted in the warmer months of the year that zooplankton tended to occur in maximum concentrations between the 20 and 30-m depth contours and then concentrations leveled off or decreased out to the 45-m depth contour. Zooplankton concentrations probably continued to decrease with increasing water depth as

the hypolimnion, with its smaller zooplankton populations, accounted for an increasingly large fraction of the water column sampled. In the following section, we consider the offshore region as consisting of two subregions, i.e. an inner offshore region between the 20 and 30-m depth contours containing large zooplankton populations and an outer offshore region beyond the 30-m depth contour and a region of decreasing zooplankton populations with increasing water depth. A fourth region, the beach region, occurred inside the 5-meter depth contour. Similar species inhabited the beach region and the inshore region although zooplankton population structure differed between the two regions. The absence of aquatic vegetation (grasses, reeds, etc.) in the beach region (Ayers and Seibel 1973) prevented a distinct species fauna from developing in this area of the lake.

Other researchers studying the aquatic community in Lake Michigan have also divided the lake into regions. Beeton and Barker (1974) using cluster analysis identified three groups of stations; the 10 and 20-m depth contours generally separated the three groups. The Great Lakes Fishery Laboratory (1970) identified the 100-foot (30 m approximately) depth contour as the boundary between the inshore and offshore regions and identified the 30-foot (10 m approximately) depth contour as a boundary subdividing the inshore region. Morsell and Norden (1968) used these depth contours and a third, the 4-foot depth contour (1 m approximately) to delineate the shore region; these differences in region locations were based on observed differences in alewife feeding behavior. These depth-defined regions of the lake correspond well with the location of our beach, inshore, middle, and offshore regions.

Regional differences in community structure indicate that the magnitude of ecological parameters varies spatially in Lake Michigan. Zooplankton inhabiting the water within the 10-m depth contour generally experience different predation pressures, thermal regimes, and food availability than populations inhabiting the middle and offshore regions. These differences in ecological parameters may result in different power plant impacts in different regions of the lake. This recognition focused our attention from the entire survey grid to the inshore region for our analyses of preoperational and operational zooplankton distributions (Section 2). Zooplankton inhabiting the inshore region are subject to condenser passage and plume entrainment and are more likely to experience direct effects (mortality or sublethal damage due to mechanical or thermal stresses) of power plant operation. In the middle and offshore regions, power plant effects are more likely to be indirect involving biological routes (predation, competition, food availability).

SECTION 2

EVALUATION OF THE EFFECTS OF PLANT OPERATION ON ZOOPLANKTON POPULATIONS IN SOUTHEASTERN LAKE MICHIGAN DURING 1975 AND 1976

INTRODUCTION

Survey cruises conducted in 1975 and 1976 provide information on zooplankton populations in southeastern Lake Michigan during operation of Unit 1 of the Donald C. Cook Nuclear Power Plant. Cruises conducted prior to 1975 (1969 to 1974) provide comparative information on zooplankton populations before plant operation. The purpose of this section is to evaluate differences in zooplankton populations between the preoperational and operational periods over a 250 km² area of southeastern Lake Michigan. Differences which occurred in the area near the plant site and in the upcurrent and downcurrent reference areas are of particular interest.

One of the earliest concerns about power plant operation was that the thermal plume would disrupt zooplankton temporal succession patterns causing typical summer species to appear earlier in the plankton and to persist through the autumn. A second concern was that power plant operation would produce localized changes in zooplankton community structure associated with increased numbers of pollution tolerant, nuisance, or otherwise non-typical taxa. Preliminary indications of plant effects can be ascertained by simple graphical analyses (abundance plots, time series plots). Statistical techniques can be employed to quantify the degree of disruption or the lack of effects. Commonly employed analyses include analysis of variance, analysis of covariance, and cluster analysis.

The most common analytical approach employed in power plant studies on Lake Michigan has been to statistically compare zooplankton densities in the thermally affected area with their densities upcurrent and downcurrent from the plume. This approach tests for spatial alterations in zooplankton distributions. Studies conducted at the Bailly (Texas Instruments Incorporated 1975), Point Beach (Limnetics Incorporated 1975, 1976), Kewaunee, Zion, and Waukegan power plants (Industrial Bio-Test Laboratories Incorporated 1974 b, c, 1975) have shown various combinations of differences in zooplankton densities between the plume zone and the upcurrent and downcurrent control zones during seasonal cruises. The conclusion from these studies was that these differences merely reflected the patchy nature of zooplankton distributions rather than plant effects. We employed the spatial approach by simply graphing zooplankton densities over the survey grid by month (Section 1). Zooplankton abundances in the plume area were similar to densities in the upcurrent (south) and downcurrent (north) areas.

An alternative to comparing zooplankton distributions over a survey grid at a single point in time is to compare zooplankton distributions in the

plume area before and during plant operation (the temporal approach). Such tests may show that zooplankton occurred in higher concentrations in the plume area before plant operation. We checked for temporal changes graphically by plotting zooplankton densities in the plume area versus time. Differences, if they occurred, could be plant-related or caused by other factors such as eutrophication. Thus, comparisons must be made not only in the plume area but in control areas. This differs from the previously described approaches in that both temporal and spatial differences in zooplankton abundances due to plant operation are evaluated.

We decided to use a combined temporal-spatial approach in our statistical evaluations of the effects of Unit 1 operation of the Donald C. Cook plant. Preoperational versus operational temporal-spatial comparisons can be made in two basic ways. One test involves comparing the relationship between the plume zone and the control zones in the preoperational years with their relationship during the operational period. There are limitations to this method. First, operational changes in the relationship may result from an alteration in populations in one of the control zones rather than from changes in the plume zone. Thus it is necessary to conduct further tests to identify the source of differences. Secondly, if plume and control zones are changing in the same manner (e.g. due to lake-wide eutrophication) these changes would not be detected as long as the basic relationship between the zones remained the same. A better method is to compare zooplankton densities between the preoperational and operational periods, and do so in both the plume and control zones. This method provides indications of the absolute changes in zooplankton population in the operational years and whether or not these changes were localized near the power plant (direct plant effects) or over a wider area. The monitoring program for the D.C. Cook Plant was designed for such an analytical approach. It spans several years of preoperational and operational monitoring and covers a large survey area incorporating numerous control areas.

HISTORY OF THE SURVEY PROGRAM

The zooplankton preoperational cruises began in April 1969 and terminated in October 1974. Thirty-eight cruises were conducted; zooplankton were collected at 7 to 46 stations, and nearly 1,400 samples were examined. In 1975 and 1976, fifteen cruises consisting of 14 to 30 stations were conducted; over 660 samples were examined. Almost 50 species of copepods and cladocerans have been identified from these samples. At this point a review of the sampling program is provided and the subsets of the data used in the statistical analyses are specified.

The sampling grid, the collecting techniques, and the counting methods have improved over the years (Table 6). In the early years of the study, relatively few cruises were conducted but a large number of stations were sampled. Identifications, particularly for the cyclopoid copepods, were to a low level of taxonomic resolution. Recently, more cruises have been conducted but fewer stations have been sampled during each cruise. Zooplankton have been identified to an increasingly higher level of taxonomic resolution. The mesh size of the nets used in collecting zooplankton, the number of replicate hauls made at each station, and the subsampling techniques have also varied over the years. Since 1974, no substantial changes have been made in methods.

Stations

The number of stations sampled during a cruise has varied from a minimum of 7 during the 1972 and 1973 short survey cruises to a maximum of 46 in the original (1970 - April 1972) major survey grid. Beginning in 1972, short surveys consisting of 8 stations were initiated to provide supplemental information on zooplankton population dynamics. At this time, the major survey grid was reduced to 28 stations. Construction of the discharge structure prevented sampling at station DC-1 during most of 1972 and 1973.

Dredging and the construction of a temporary safe harbor during this time may have produced local changes in lake currents in what is now the thermal plume region. Since 1974, the number of major and short survey stations has remained unchanged at 30 and 14 respectively, except as noted below. In October 1975 and 1976, three or four of the outermost stations were not sampled due to hazardous lake conditions. Major instead of short surveys were conducted in August 1975 and May 1976 following major surveys conducted during plant shutdown. Poor weather and hazardous lake conditions have prevented November cruises from being conducted in most years.

Only data collected during the April, July, and October major survey cruises (27 to 30 stations) were used in the statistical analyses. Too few stations were sampled during the short survey cruises to justify statistical comparisons between the preoperational and operational periods. Data from both major surveys and short surveys were used to delineate zooplankton succession patterns in the plume region; however, too few stations were

TABLE 6. Summary of the field survey sampling program.

		Preoperational Years					Operational Years	
		69	70	71	72	73	74	75
Apr	Number of stations sampled	9		46	46	27	28	30
	Net mesh (μ)	282		158	158	158	158	158
	Replicates counted per station	1		1	1	3	2	2
May	Number of stations sampled			8	7	14	14	30
	Net mesh (μ)			158	158	158	158	158
	Replicates counted per station			1	3	2	2	2
Jun	Number of stations sampled			8	158	14	14	14
	Net mesh (μ)			158	158	158	158	158
	Replicates counted per station			1	3	2	2	2
Jul	Number of stations sampled	46	46	28	27	30	30	30
	Net mesh (μ)	282	158	158	158	158	158	158
	Replicates counted per station	1	1	1	3	2	2	2
Aug	Number of stations sampled			7	7	14	30	14
	Net mesh (μ)			158	158	158	158	158
	Replicates counted per station			1	3	2	2	2
Sep	Number of stations sampled	46	46	7	7	14	14	14
	Net mesh (μ)	282	158	158	158	158	158	158
	Replicates counted per station	1	1	1	3	2	2	2
Oct	Number of stations sampled			27	27	30	27	26
	Net mesh (μ)			158	158	158	158	158
	Replicates counted per station			1	3	2	2	2
Nov	Number of stations sampled	46	46	7				
	Net mesh (μ)	282	158	158				
	Replicates counted per station	1	1	1				
Dec	Number of stations sampled						14	
	Net mesh (μ)						158	
	Replicates counted per station						2	

sampled in the northern and southern control areas during the short surveys cruises to justify similar preoperational and operational comparisons.

Nets

A number 5 mesh net (282μ) was used in 1969 and 1970, and a number 10 net (158μ) was used in 1971 and continues to be used for the operational zooplankton surveys. The 1969 and 1970 data were not used in the analyses because of the lack of comparability of these data with data collected using the finer mesh net.

Replicate samples

A single haul net was made at each station in 1971 and 1972. Since 1972, three replicate hauls were made at each station. However, only two of the replicate samples were generally counted from 1974 to 1976.

Subsampling techniques

Samples collected between 1969 and 1971 were subdivided with a Stempel pipette. Up to fifteen 1-ml subsamples were counted in each sample. A Folsom splitter was also used to subsample some of the 1971 samples. Density estimates were comparable to those obtained with the pipette (Roth 1973). The Folsom splitter has been used since 1971. Methods of use are described in Section 1.

Taxonomic identifications

The level to which zooplankton were identified has varied with the taxon, the year, and the station (Table 7). Most cladocerans were identified to genus beginning in 1970 although Eubosmina sp. and Bosmina sp. were enumerated as Bosminidae until 1972. Species identifications were made at three stations (DC-2, DC-5, DC-6) in 1972 and 1973 and at an increasing number of stations in 1974. Beginning in 1975, identifications have been to species at all 14 short survey stations and at 22 of the 30 major survey stations (Fig. 1).

Adult calanoid copepods and cladocerans were identified to genus at most preoperational stations and to species at most operational stations. Copepods were also sexed at most stations beginning in 1974 although this additional information has not yet been fully analyzed. Immature calanoid copepodites were combined as a group until 1973. Since then they were identified to genus.

Cyclopoid cyclopods generally were combined as a group until 1973 although immatures and adults were distinguished at three stations beginning in 1972; adults were identified to species level and immatures to genus level. Since April 1973, adult Cyclops spp. have been separated from

TABLE 7. Taxonomic resolution of zooplankton counts made between 1971 and 1976. Years in which taxa are counted at all stations (or at all "species" stations since 1973) are shown as solid lines, years in which taxa are counted at only a few stations (i.e. DC2, DC5 and DC6) are shown as dashed lines, and years in which taxa were not counted are blank.

Taxon	Year				
	1971	1972	1973	1974	1975
Copepod nauplii	---	---	---	---	---
Cyclopoid C1-C6	---	---	---	---	---
Cyclopoid C1-C5	---	---	---	---	---
<u>Cyclops</u> spp. C1-C5	---	---	---	---	---
<u>Tropocyclops</u> sp. C1-C5	---	---	---	---	---
Cyclopoid C6	---	---	---	---	---
<u>Cyclops</u> spp. C6	---	---	---	---	---
<u>Cyclops bicuspidatus thomasi</u> C6	---	---	---	---	---
<u>Cyclops vernalis</u> C6	---	---	---	---	---
<u>Tropocyclops prasinus mexicanus</u> C6	---	---	---	---	---
all other cyclopoid species	---	---	---	---	---
Calanoid C1-C6	---	---	---	---	---
Calanoid C1-C5	---	---	---	---	---
<u>Diaptomus</u> spp. C1-C5	---	---	---	---	---
<u>Epischura</u> sp. C1-C5	---	---	---	---	---
<u>Eurytemora</u> sp. C1-C5	---	---	---	---	---
<u>Limnocalanus</u> sp. C1-C5	---	---	---	---	---
Calanoid C6	---	---	---	---	---
<u>Diaptomus</u> spp. C6	---	---	---	---	---
<u>Diaptomus ashlandi</u> C6	---	---	---	---	---
<u>Diaptomus minutus</u> C6	---	---	---	---	---
<u>Diaptomus oregonensis</u> C6	---	---	---	---	---
<u>Diaptomus sicilis</u> C6	---	---	---	---	---
<u>Epischura lacustris</u> C6	---	---	---	---	---
<u>Eurytemora affinis</u> C6	---	---	---	---	---
<u>Limnocalanus macrurus</u> C6	---	---	---	---	---
all other calanoid species	---	---	---	---	---
Harpacticoid C1-C6	---	---	---	---	---
<u>Bryocamptus</u> spp. C1-C5	---	---	---	---	---
<u>Bryocamptus</u> spp. C6	---	---	---	---	---
<u>Canthocamptus</u> spp. C1-C6	---	---	---	---	---
<u>Canthocamptus</u> spp. C6	---	---	---	---	---
Cladocerans	---	---	---	---	---
Bosminidae	---	---	---	---	---
<u>Bosmina longirostris</u>	---	---	---	---	---
<u>Eubosmina coregoni</u>	---	---	---	---	---
<u>Daphnia</u> spp.	---	---	---	---	---
<u>Daphnia retrocurva</u>	---	---	---	---	---
<u>Daphnia galeata mendotae</u>	---	---	---	---	---
<u>Daphnia longiremus</u>	---	---	---	---	---
<u>Alona</u> spp.	---	---	---	---	---
<u>Alonella</u> spp.*	---	---	---	---	---
<u>Diaphanosoma</u> spp.	---	---	---	---	---
<u>Ceriodaphnia</u> spp.	---	---	---	---	---
all other cladoceran species	---	---	---	---	---
Asplanchna spp.	---	---	---	---	---

* identified as Disparalona spp. since 1976.

immatures at all stations. Tropocyclops sp. adults and immature copepodites were not distinguished until 1974. Nor were immature and adult harpacticoid copepods distinguished until 1974. Beginning in 1974, cyclopoid and harpacticoid copepods were identified to the same level of resolution as the calanoid copepods.

Copepod nauplii were combined into a single category. They were not enumerated in 1969 and 1970 when the 282 μ mesh was used. A 158 μ net has been used since 1971. However, nauplii densities are underestimated since many of the smaller cyclopoid nauplii escape through this even finer mesh net. Nauplii were not routinely counted at all stations until 1972.

The only rotifer enumerated was Asplanchna spp. Although other rotifer species occurred in the samples, their small size precluded their being sampled quantitatively by the 158 μ aperture net.

METHODS

Analytical Design of the Survey Grid

Examinations of the preoperational and operational data have shown that zooplankton vary in abundance over the survey grid, and that the greatest differences are associated with depth or distance from shore (Section 1). Our subdivision of the survey grid into four depth-related regions (Fig. 35) is supported by the results of principal component analyses and the graphical analyses of zooplankton depth-density trends. These regions are designated the inshore (5 to 10-m depth contours), the middle (10 to 20-m depth contours), the inner offshore (20 to 30-m depth contours), and the outer offshore (30 to 45-m depth contours) regions. Stations in the beach region (in water 1 to 2-m deep) were not used in the statistical analyses since they were not sampled in the preoperational period.

Although zooplankton varied in abundance along transects parallel to shore, this variation was not consistent from month to month and was probably associated with transient zooplankton patchiness. This contrasts with the benthos study where consistent differences in macrobenthic composition have been observed between the northern and southern halves of the survey grid (Mozley 1974). We could not further subdivide the survey grid on the basis of consistently observed patterns in zooplankton abundance. Further subdivisions were based on the location of the thermally detectable plume. Generally the plume was detected only within 1.6 km of the discharge site and while it generally flowed parallel to shore, it sometimes had a strong offshore component (Section 1). The inshore and middle depth regions were subdivided into plume zones, extending 1.6 km north and south of the discharge site, and into northern and southern control zones. The small number of stations in the inner and outer offshore zones precluded further subdivision of these areas (Fig. 35).

Temporal succession patterns of selected taxa in the inshore plume zone (zone 2) were examined in a series of graphs of zooplankton density versus time. These graphs facilitate comparisons of zooplankton temporal succession patterns and reveal the magnitude of temporal variations in zooplankton populations in the inshore plume zone. Statistical analyses comparing zooplankton abundances between the preoperational and operational periods were the major tests used in evaluating plant effects. These temporal-spatial statistical analyses utilized the major survey data and compared zooplankton abundances by zone and by month between the preoperational and operational periods.

Statistical Test Design

The data set was stratified into preoperational and operational blocks and station density estimates were compared using the Mann-Whitney U test (Siegel 1956; Conover 1971). These comparisons were made separately for each

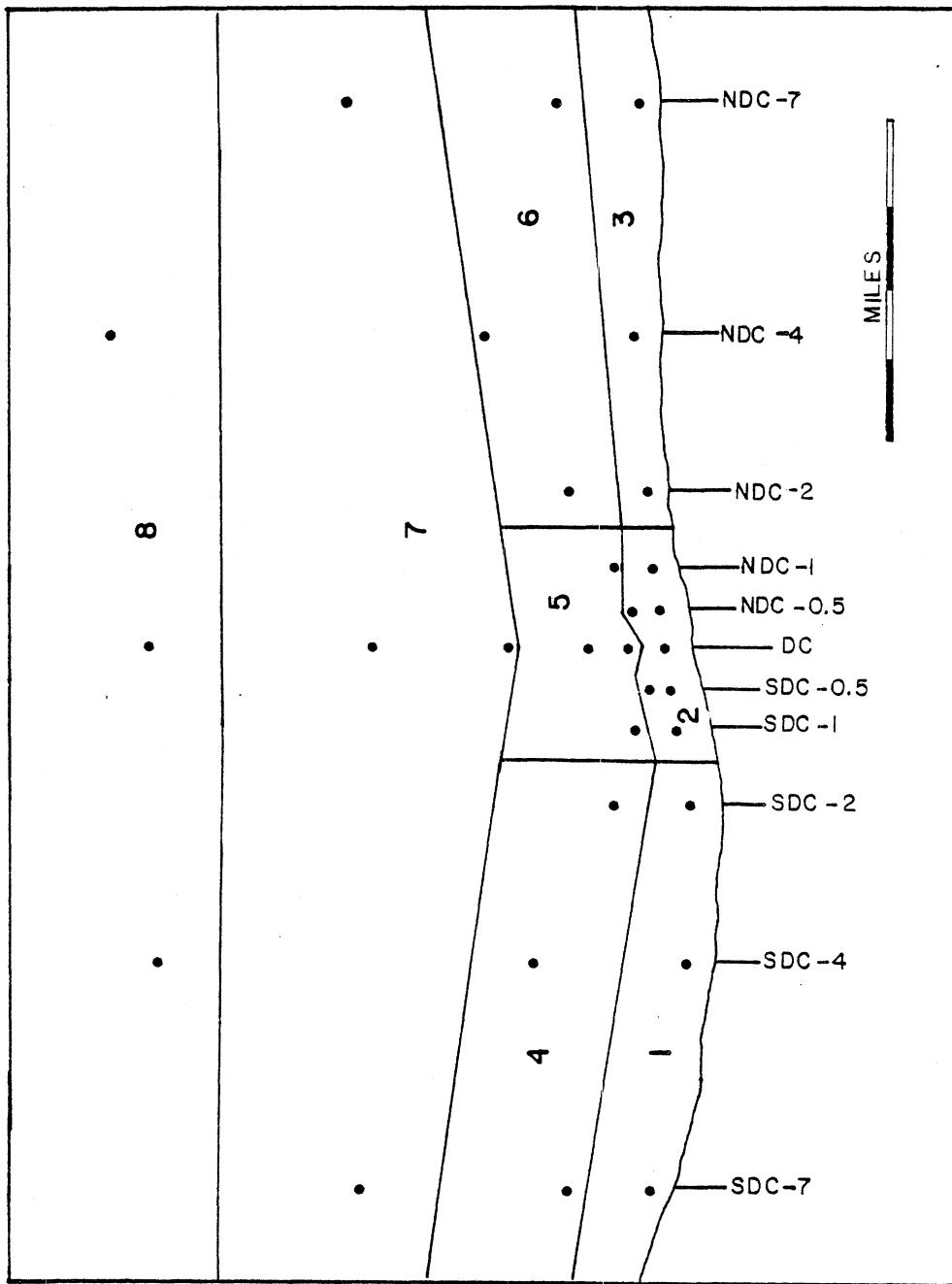


FIG. 35. Thirty-station major survey grid divided into the eight zones used in the pre-operational and operational comparisons.

month and zone in order to eliminate spatial and temporal variability which was irrelevant to our investigation of power plant impact. The Mann-Whitney U test is a non-parametric procedure based on the ordered ranks of the data. A two-sided test was used to evaluate the zone densities before and during plant operation. The power efficiency of the Mann-Whitney U test is at least 86% that of the parametric t-test and is generally higher when the data are not normally distributed (Conover 1971).

The assumptions underlying the Mann-Whitney U test appear to have been met. The samples were independent and drawn randomly from the zooplankton populations at each station. The density estimates represented continuous random variables and the measurement scale was at least ordinal. The third assumption was that the control and experimental populations differed only in the location of their mean.

Parametric tests for detecting differences between populations such as Student's t-test and the analysis of variance were not used. Their assumptions of normality and/or equality of variance could not be met by all the data. Both $\log_{10} (\#/m^3 + 1)$ and square root transformation of the density estimate failed in most cases to result in normality and equality of variance.

Calculations were performed on the AMDAHL 470V/6 computer at the University of Michigan using the TWO SAMPLE program incorporated into MIDAS. Zone densities differing at the 95% confidence level were considered significant. Monthly zone densities were calculated for each taxon in the preoperational and operational period as were the 95% confidence intervals for the differences between the means (Appendix, Tables 42-44).

Zooplankton Taxa tested

Although nearly 50 species of zooplankton have been identified in the survey area, it was neither practical nor necessary to analyze the distributions of all taxa. We used the guidelines set by the Michigan Department of Natural Resources in selecting taxa to be considered in evaluating the effects of plant operation on "the maintenance of a balanced indigenous population in the discharge area." The department recommended that the following categories of zooplankton be considered for preoperational and operational comparisons:

- (1) those taxa which account for 10% of the zooplankton by weight or by numbers in each of the four seasons
- (2) threatened or unique species
- (3) pollution-tolerant species
- (4) temperature-sensitive species
- (5) nuisance-potential species
- (6) species of significance to public health
- (7) species indicative of certain water quality or environmental conditions

(8) species of historical significance.

They further recommended that all life forms and activities (adults, juveniles, growth, feeding, etc) be evaluated.

The numerically dominant species in the spring, summer, autumn, and winter have been identified (Section 1) as Cyclops spp., Diaptomus spp., their nauplii, Bosmina longirostris, Eubosmina coregoni, and Daphnia spp. Potentially pollution-tolerant zooplankton include Cyclops bicuspidatus thomasi and Bosmina longirostris. A number of other species thrive in shallow, polluted waters (C. vernalis, Eury cercus lamellatus, Alona spp., Chydorus sphaericus). However, they are generally rare in the plankton in the survey area (Table 3). The error associated with estimating concentrations of these rare taxa is so large that only extremely large differences in the concentrations of these taxa would be detectable with the two-year operational data base. Visual comparisons of the preoperational and operational data did not reveal such differences, so the data were not further subjected to statistical analyses.

Temperature sensitive zooplankton include Limnocalanus macrurus and Daphnia longiremis and possibly Diaptomus sicilis. Statistical analyses were performed only for L. macrurus in April. The preoperational data base for D. longiremis and D. sicilis was not adequate for statistical comparisons since Daphnia spp. and Diaptomus spp. were identified to species at only a limited number of stations.

All zooplankton are important in energy transfer but at this time it is not possible to quantify the importance of each species. The numerically dominant herbivores (Diaptomus spp., Bosmina sp., Eubosmina sp., Daphnia spp.) were used in the analyses but the rarer copepod and cladoceran herbivores were not. The only omnivores sufficiently abundant for statistical analyses were Limnocalanus sp. and Cyclops spp. Carnivorous zooplankton such as Polyphemus pediculus, Leptodora kindtii, and adult Epischura lacustris were not sufficiently abundant to merit statistical analysis. Asplanchna spp., a carnivorous rotifer, was occasionally abundant and preoperational and operational comparisons were made for this genus in selected months.

There are no zooplankton in categories 2, 5, 6, and 8. The monitoring program was not designed to measure zooplankton physiological processes such as growth, feeding, etc.

Comparisons were made at several taxonomic levels. Order and suborder classifications (i.e. Cladocera, Cyclopoida, Calanoida) were used in order to utilize the largest possible preoperational data set (1971-1974) for making preoperational versus operational comparisons. Comparisons at the genus or species level and for immature and adult copepods could be made only with a two or three year subset of the subset of the preoperational data base.

RESULTS

Temporal Abundance Patterns of Zooplankton in Zone 2 (1971-1976)

The temporal abundance patterns of the nine most common zooplankton taxa in zone 2 (Fig. 36) were examined to determine the major features of their seasonal cycles and to compare these features between the preoperational and operational periods. Overall, the temporal succession patterns were similar during the preoperational and operational periods. The range of population densities observed during the preoperational period were not exceeded in the operational period. Similarly, the range of variation in timing of the events of the seasonal cycle has not been exceeded in the operational period. The most important details of the seasonal population cycles are reported below.

Zooplankton were highly seasonal in abundance. Some taxa such as Limnocalanus macrurus were generally observed in zone 2 only in April (Section 1). Cyclops spp., Diaptomus spp., Eurytemora affinis, and cladoceran populations (Fig. 36) were generally small in April or May and occurred in maximum concentrations in the warmer months of the year. The number of population peaks and their timing varied between years. For example, cyclopoid copepods had one (1973), two (1972, 1974) or three (1975) population pulses each year with peak concentrations occurring between July and September. Bosmina longirostris represented another extreme; August populations may represent a seasonal maximum (greater than $130,000/m^3$) as in 1972 or a minimum (less than $1,000/m^3$) as in 1973. The maximum seasonal density of total zooplankton was extremely variable between years ranging from less than $30,000/m^3$ in 1974 to over $180,000/m^3$ in 1972.

Month-to-month variations in zooplankton numbers were particularly large during the warmer summer and autumn months. For example, the cladoceran Bosmina longirostris increased from less than $1,000/m^3$ in June 1972, to over $45,000/m^3$ the following month, and attained a mean zone concentration of over $130,000/m^3$ in August. High fecundity and short generation times during the summer and autumn months can result in zooplankton populations increasing dramatically over a matter of days. At these times, it is questionable whether surveys conducted once a month provide accurate estimates of mean zooplankton population sizes during the 30-day interval between cruises. In Section 4, we present data which indicate that zooplankton can exhibit as much variation from week to week as from month to month.

The standard errors of the zone means indicate the amount of spatial variability in zooplankton density. These standard errors were frequently large indicating much between-station variance in zone 2. Zone 2 contained a maximum of 7 stations and the estimates of the zone mean and variance were more accurate in this zone than in the other seven zones of the survey grid where only 3 to 5 stations were generally sampled. These within-zone spatial variations in zooplankton abundance reduce the likelihood of detecting

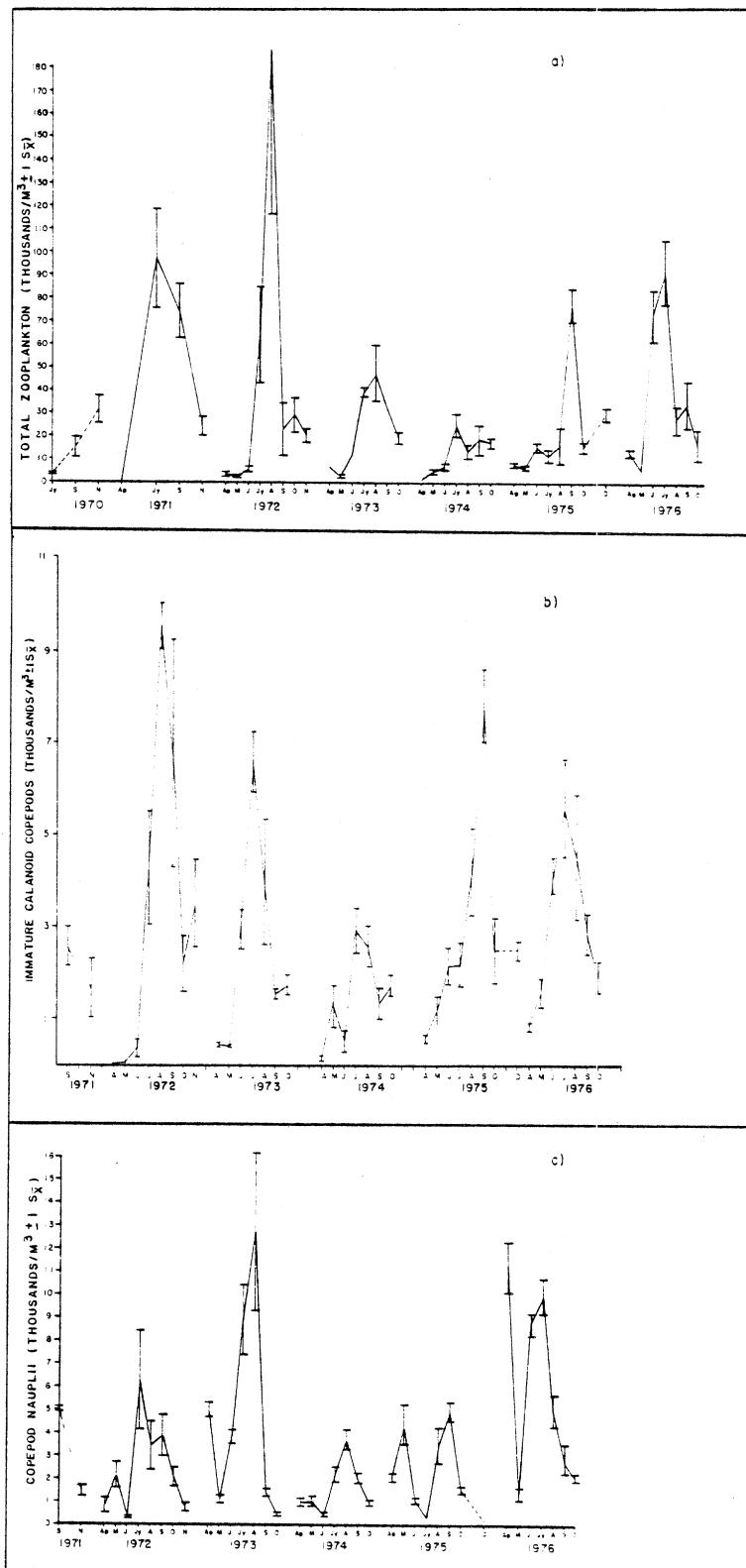


FIG. 36. The monthly abundance of zooplankton in the inshore plume zone (zone 2) between 1970 and 1976. a) Total zooplankton, b) immature calanoid copepods, c) copepod nauplii.

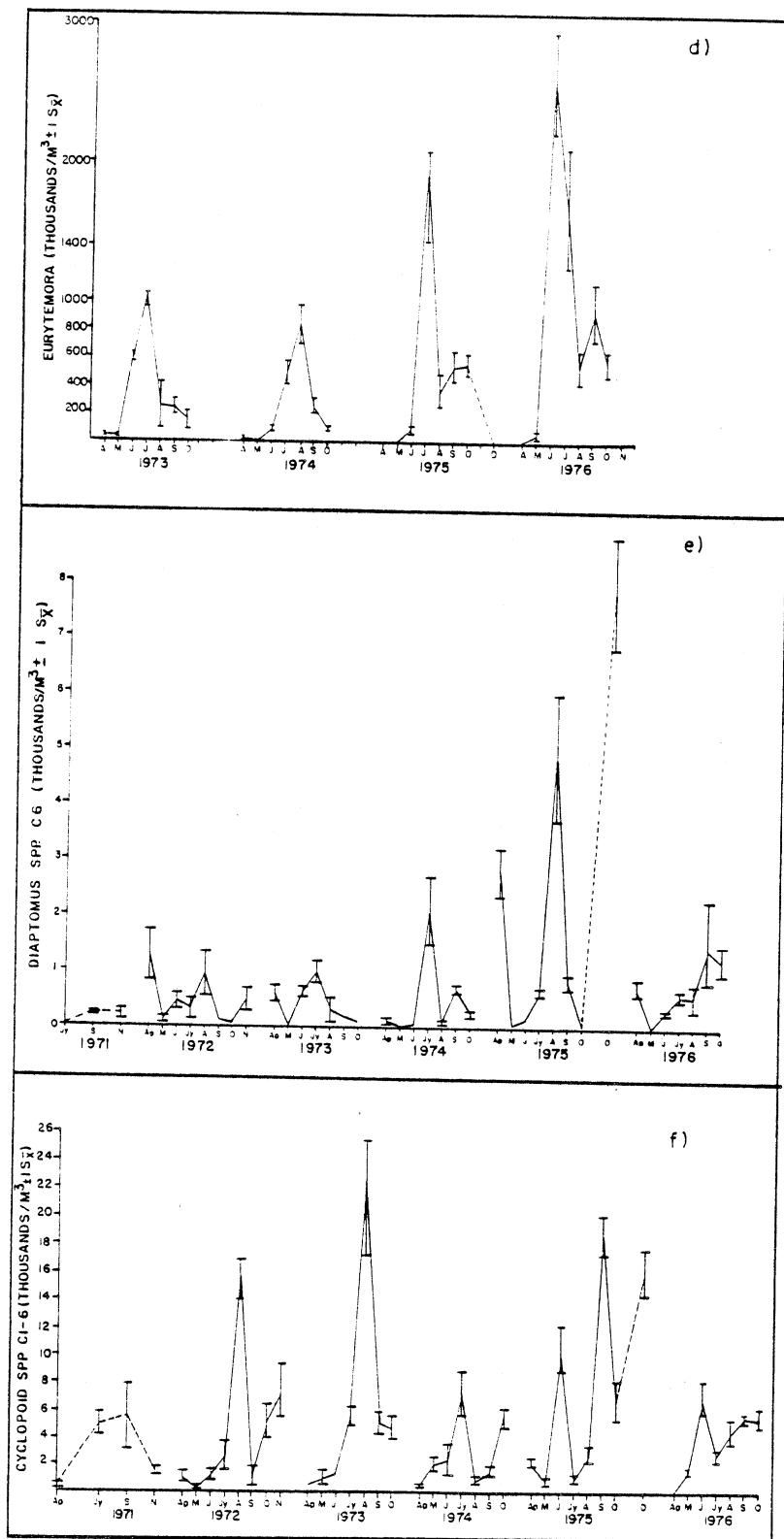


FIG. 36 continued. d) Eurytemora affinis, e) Diaptomus spp. C6, f) cyclopoid copepods.

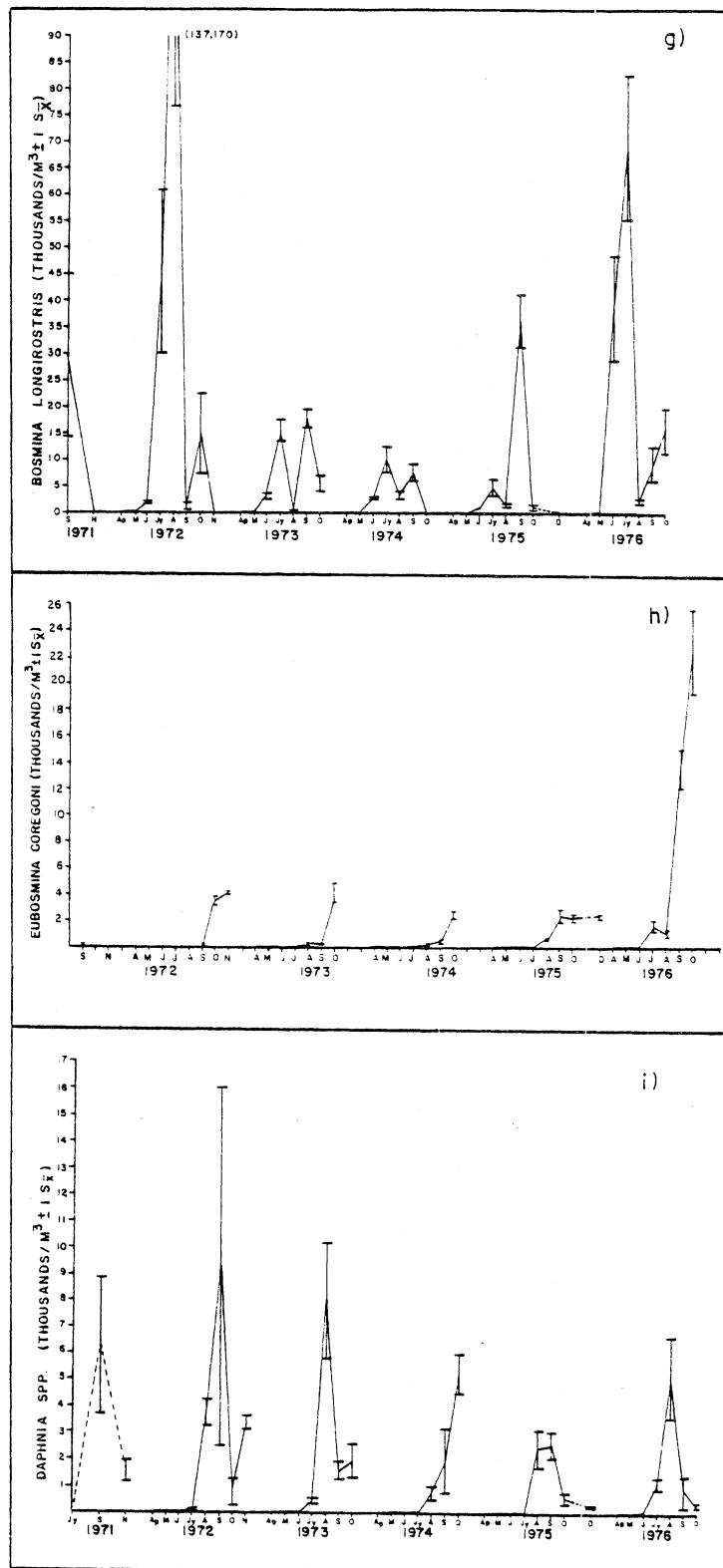


FIG. 36 continued. g) *Bosmina longirostris*, h) *Eubosmina coregoni* and i) *Daphnia* spp.

statistically significant temporal differences in zooplankton abundance.

Some qualitative and quantitative differences were observed. Total zooplankton populations declined between June and July in 1975 (but not 1976); this was not observed in the preoperational period. The 1975 and 1976 spring nauplii pulse was large and similar in size to the autumn pulse; spring nauplii populations in zone 2 were smaller in the preoperational period. Adult Diaptomus spp. were more numerous in August 1975 and in September and October 1976 than in the preoperational period. Cyclopoid copepodites occurred in peak concentrations in June (1975, 1976) rather than July or August as in the preoperational years. Eurytemora affinis was more abundant in 1975 and 1976 and there was some evidence of a secondary autumn pulse; populations may have commenced to increase one month earlier in 1976 than in 1975 or in the preoperational years. Bosmina longirostris and Daphnia spp. generally occurred in similar seasonal patterns in the preoperational and operational periods although the summer 1976 population increase may have commenced one month earlier. Eubosmina coregoni was particularly abundant in the autumn of 1976 and the summer increase in numbers appeared to commence one month earlier in this year. In the following paragraphs, we evaluate the quantitative differences in zooplankton taxa abundances in zone 2 between the preoperational and operational periods for April, July, and October. Similar evaluations are made in the control zones in order to distinguish between plant-caused impacts and natural variations in zooplankton numbers.

Statistical Comparisons of April Preoperational and Operational Abundances

The preoperational and operational abundances in April for nine zooplankton taxa were compared by using the Mann-Whitney U test. Apart from the three cyclopoid categories, the remaining six zooplankton taxa occurred in significantly ($\alpha = .05$) different concentrations between the preoperational and operational periods (Table 8). Significant differences were detected not only in the inshore and middle plume zones (2, 5) but also in the southern and northern control zones (1, 3, 4, 6) and the inner offshore zone (7). Only in the outer offshore zone were zooplankton abundances statistically equal in the preoperational and operational periods. Nauplii, and immature and adult Diaptomus spp. and Limnocalanus macrurus copepodites all occurred in significantly different concentrations in some zones of the survey grid in the operational period when compared with their preoperational abundances.

Total zooplankton were approximately 1.4 to 3 times more abundant in zones 1 to 7 in the operational period than in the preoperational period (Fig. 37), and the greatest increases occurred in the two plume zones (2, 5). The higher operational period densities were the result of high zooplankton densities throughout the survey area in April 1976; densities in 1975 were more nearly equal to densities recorded in the preoperational period. The power plant was not operational during the April 1976 cruise although it did produce heated water in the days prior to the cruise.

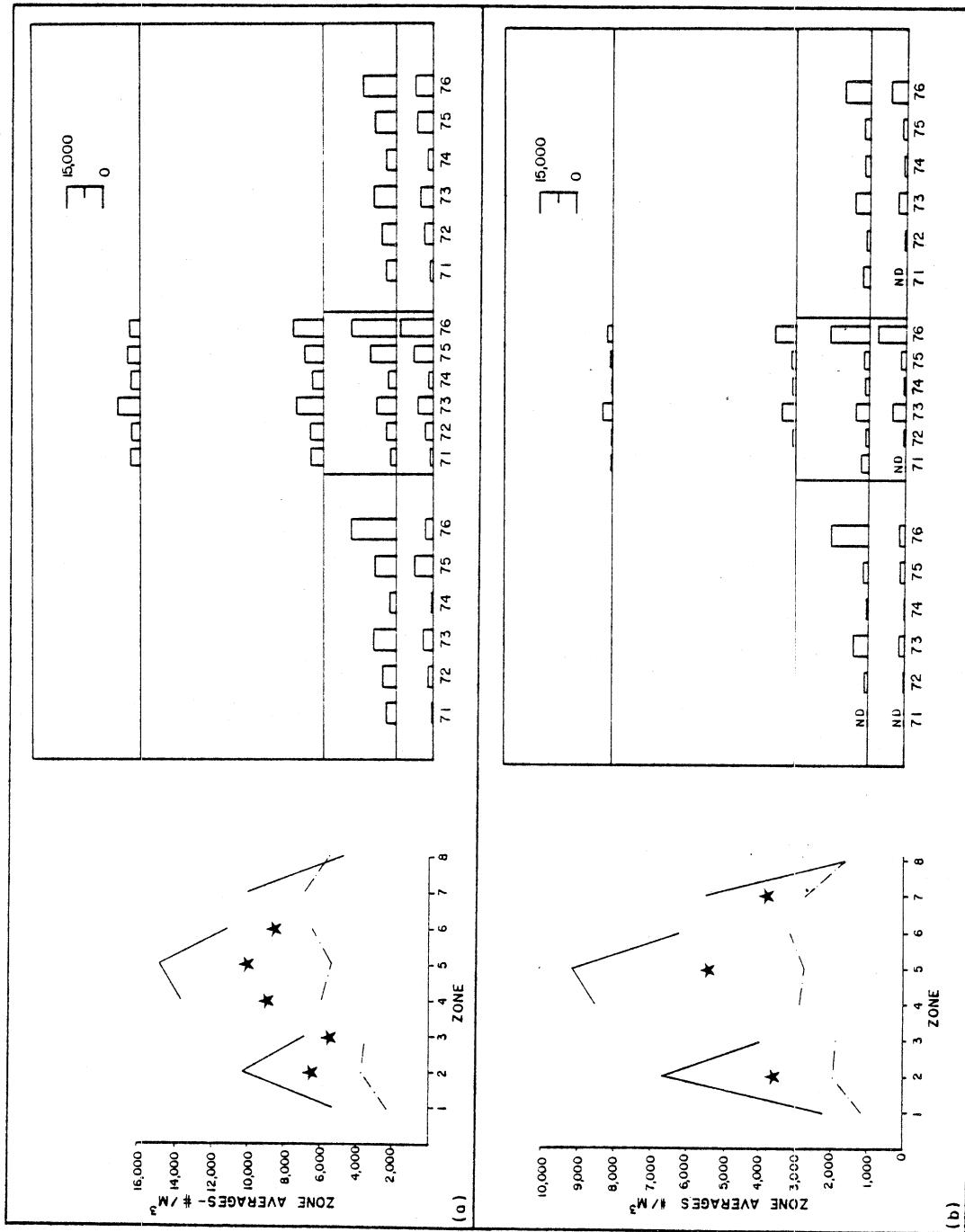


FIG. 37. The mean densities of zooplankton taxa in April of each year, 1971-1976, are given in the histograms. The mean preoperative and operative period (dashed and solid lines, respectively) densities are plotted for each zone. Lines connect zones in the same depth grouping, inshore, middle, and inner and outer offshore zones. Stars indicate zones with significantly different preoperative and operative densities (Mann-Whitney U test = 0.05).
 a) Total zooplankton, b) copepod nauplii.

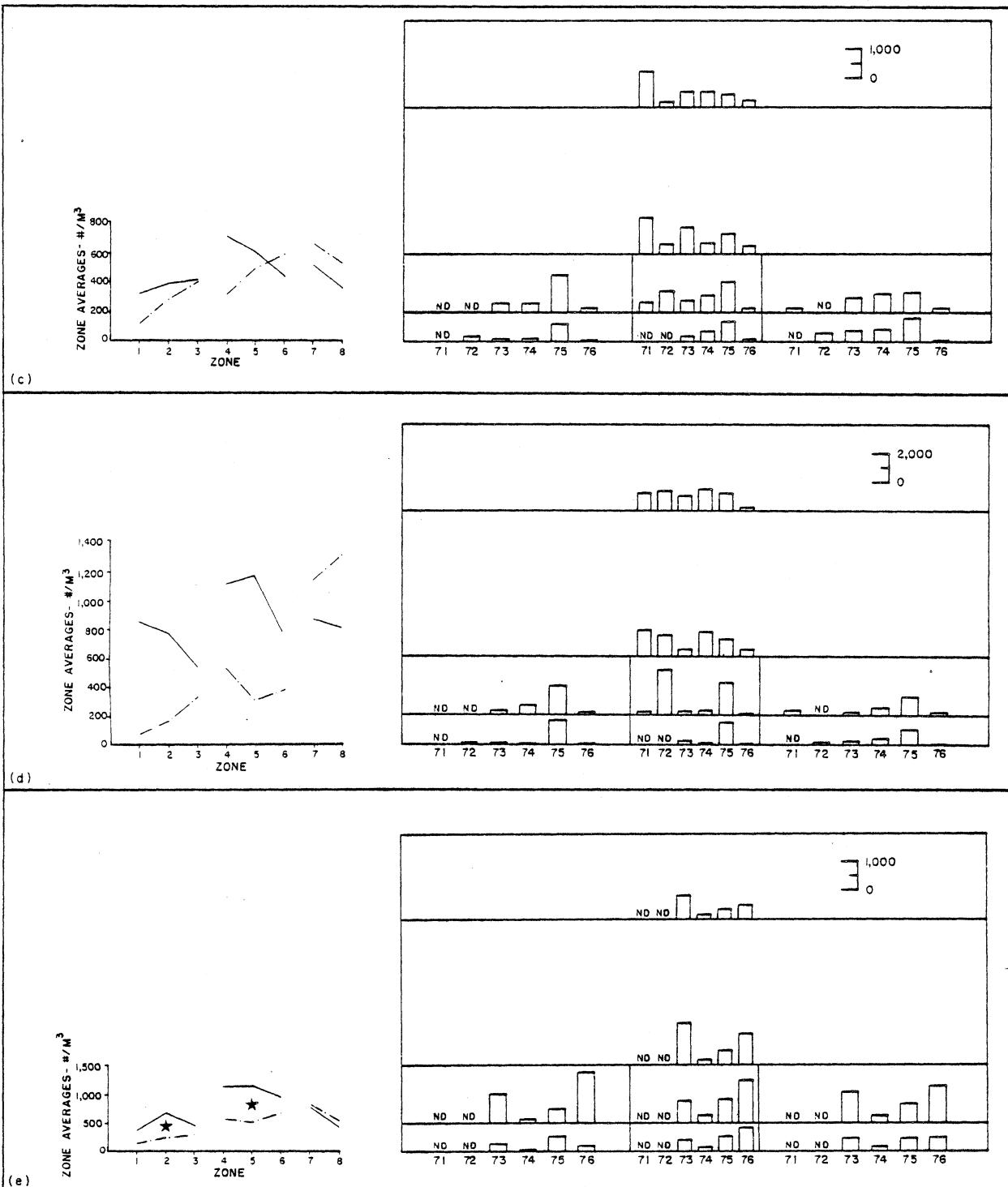


FIG. 37 continued. c) immature cyclopoids, d) adult Cyclops spp., e) immature Diaptomus spp.

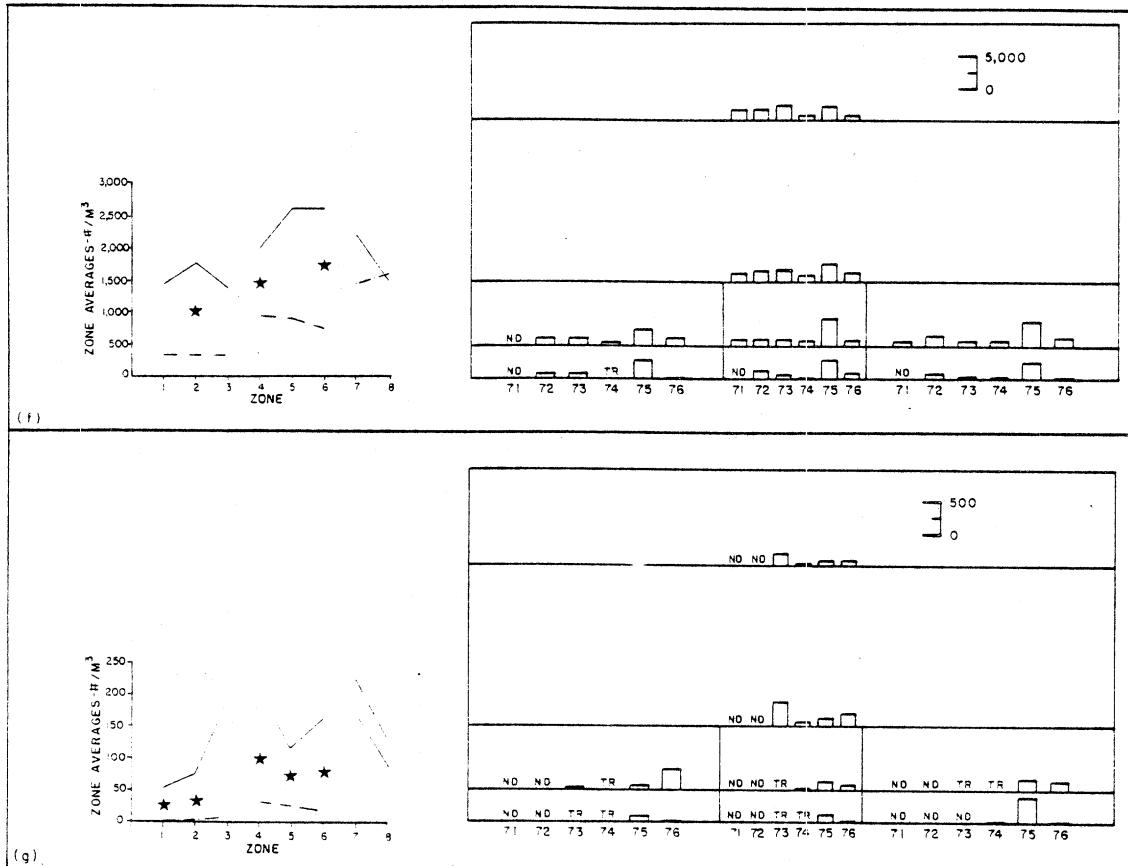


FIG. 37 continued. f) adult Diaptomus spp. and g) Limnocalanus macrurus.

Nauplii (Fig. 37) were the numerically dominant taxon over most of the survey grid and occurred in higher concentrations in the operational years (except for zone 8), although differences were statistically significant only in zones 2 and 5 (the two plume zones) and zone 7. High concentrations of nauplii in April 1976 were the major factor for the increased operational zone mean concentrations. Nauplii concentrations were lower in April 1975 and were comparable to populations in the preoperational period.

Immature and adult Diaptomus spp. (Fig. 37) were also more abundant in the operational period. Immature copepodite concentrations were significantly different only in the inshore and middle plume zones while adult concentrations were different in the inshore plume and the northern and southern middle zones. Immatures were particularly abundant in 1976 while adults were abundant in 1975. Limnocalanus macrurus, another calanoid copepod and a cold water stenotherm, occurred in significantly higher concentrations (by a factor ranging from 5 to 90) over most of the inshore and middle regions during the operational period.

While adult Cyclops spp. (Fig. 37) were several times more abundant in the inshore and middle zones in the operational years and less abundant in the offshore zones, these differences were not statistically significant.

Immatures were more abundant in the inshore zone and the middle southern and plume zones and less abundant over the remainder of the survey grid but these differences were not statistically significant.

Statistical Comparisons of July Preoperational and Operational Abundances

The preoperational and operational abundances of thirteen zooplankton taxa were compared for each of the eight zones of the survey grid. While total zooplankton (Table 9) occurred in statistically equal concentrations between the preoperational and operational Julys (except in zone 8), several zooplankton taxa occurred in significantly different concentrations. Differences were detected in the inshore plume zone, the middle plume zone, in the northern and southern control zones, and in the inner and outer offshore zones.

Cladocerans occurred in statistically equal concentrations over the survey grid (Table 8) except in zone 8 where the operational mean concentration was less than half the preoperational mean. The numerically dominant cladoceran Bosmina longirostris (Fig. 38) was more abundant in the inshore zones and zones 4 and 7 in the operational period and less abundant in the remaining zones in 1975 and 1976; however these differences were statistically significant only in the outer offshore zone. While Bosmina longirostris tended to increase in abundance from the inshore region to the offshore region in the preoperational period, the reverse pattern was observed in the operational period; this reversal in zone mean concentrations occurred primarily in 1976. Daphnia spp. was a cladoceran of secondary numerical importance in July. It was 3 to 10 times more abundant in the operational period although these increases were not statistically significant in the northern inshore, and the northern and plume middle zones. Daphnia spp. were particularly abundant in 1976 when zone mean concentrations exceeded means observed in previous years.

Cyclopoid copepods were abundant over some areas of the survey grid. Immatures were the most common form (Fig. 38) and were 1.4 to 5.6 times more abundant in the preoperational period. Differences were statistically significant only in the inshore and middle plume zones and in the outer offshore zone. Concentrations were lower in July 1975 and 1976. Adult concentrations (Fig. 38) were also lower (except in zone 7) but the differences were statistically significant only in the three inshore zones.

Calanoid copepods occurred in significantly different concentrations (Table 9) only in the inshore plume zone. The numerically dominant taxon was Diaptomus spp. Immatures (Fig. 38) occurred in lower concentrations (by a factor of two) in the inshore and middle zones although the differences were significant only in the plume zones. Similar differences were observed for adults (Fig. 38). Eurytemora affinis was two to five times more abundant in the operational period; these differences were statistically significant in

TABLE 8. Results of the Mann-Whitney U test comparing April preoperational and operational densities of nine zooplankton taxa in each of eight zones. The preoperational period is 1971-74 or a subset ending in 1974, and the operational period is 1975-76. Sample sizes are given in Appendix Table 42.

Taxon	Zone								Period
	1	2	3	4	5	6	7	8	
Order and Suborder Level									
Copepod Nauplii	NS	*	NS	NS	*	NS	*	NS	72-76
Cyclopoids (C1-C6)	NS	NS	NS	NS	NS	NS	NS	NS	71-76
Calanoids (C1-C6)	NS	*	*	*	*	*	*	NS	71-76
<u>Genus and Developmental Stage</u>									
Cyclopoids (C1-C5)	NS	NS	NS	NS	NS	NS	NS	NS	73-76
<u>Cyclops</u> spp. C6	NS	NS	NS	NS	NS	NS	NS	NS	73-76
<u>Diaptomus</u> spp. (C1-C5)	NS	*	NS	NS	*	NS	NS	NS	73-76
<u>Diaptomus</u> spp. C6	NS	*	NS	*	NS	*	NS	NS	73-76
<u>Limnocalanus macrurus</u> (C1-C6)	*	*	NS	*	*	*	NS	NS	73-76
Total zooplankton	NS	*	*	*	*	*	NS	NS	72-76

* significant difference, $\alpha = 0.05$

NS not significant

all zones except 4, 6, and 8. Numbers were higher both in 1975 and 1976 and similar magnitudes of change were observed in plume and control zones.

Copepod nauplii occurred in statistically equal concentrations between the preoperational and operational years (Fig. 38) although nauplii were less abundant in the inshore zone and more abundant in the middle and offshore zones in the preoperational period. Asplanchna spp. was more abundant in the preoperational period (Fig. 38) although preoperational and operational differences in zone concentrations were not statistically significant.

Statistical Comparisons of October Preoperational and Operational Abundances

The preoperational and operational abundances of twelve zooplankton taxa were examined for seven zones of the survey grid. Zone 8 (outer offshore zone) was not sampled during the October 1975 and 1976 cruises due to hazardous lake conditions. All taxa occurred in statistically significant different concentrations (Table 10) between the preoperational and operational periods in at least one zone of the survey grid.

TABLE 9. Results of the Mann-Whitney U test comparing July preoperational and operational densities of thirteen zooplankton taxa in each of eight zones. The preoperational period is 1971-74 or a subset ending in 1974, and the operational period is 1975-76. Sample sizes are given in Appendix Table 43.

Taxon	Zone							Period	
Order and Suborder Level	1	2	3	4	5	6	7	8	
Cladocerans	NS	NS	NS	NS	NS	NS	NS	*	71-76
Copepod nauplii	NS	NS	NS	NS	NS	NS	NS	NS	72-76
Cyclopoids (C1-C6)	NS	*	NS	NS	*	NS	NS	*	71-76
Calanoids (C1-C6)	*	NS	71-76						
<u>Genus, Species, developmental stage level</u>									
<u>Bosmina longirostris</u>	NS	NS	NS	NS	NS	NS	NS	*	72-76
<u>Daphnia</u> spp.	*	*	NS	*	NS	NS	*	*	71-76
Cyclopoids (C1-C5)	NS	*	NS	NS	*	NS	NS	*	73-76
<u>Cyclops</u> spp. C6	*	*	*	NS	NS	NS	NS	NS	73-76
<u>Diaptomus</u> spp. (C1-C5)	NS	*	NS	NS	*	NS	NS	NS	73-76
<u>Diaptomus</u> spp. C6	NS	*	NS	*	NS	NS	NS	NS	73-76
<u>Eurytemora affinis</u> (C1-C6)	*	*	*	NS	*	NS	*	NS	73-76
<u>Asplanchna</u> spp.	NS	NS	NS	NS	NS	NS	NS	NS	71-76
Total zooplankton	NS	NS	NS	NS	NS	NS	NS	*	72-76

* significant difference, $\alpha = 0.05$

NS not significant

Cladocerans were more abundant in the operational period although differences were significant only in the northern middle zone and the inner offshore zone. Bosmina longirostris and Eubosmina coregoni were the numerically dominant cladocerans. B. longirostris (Fig. 39) occurred in significantly higher concentrations (by a factor of two) in zone 7 in the operational period while E. coregoni was three to seven times more abundant over the survey grid in the operational period. However, these differences were not statistically significant in the three inshore zones. Eubosmina coregoni numbers were particularly high in 1976. Daphnia spp. was of minor abundance in October. This cladoceran occurred in lower concentrations in the operational period although the differences were statistically significant only in zones 2, 3, and 5. Daphnia spp. were less abundant both in 1975 and 1976 in comparison to their preoperational abundances.

Cyclopoid copepods were more abundant in the operational period,

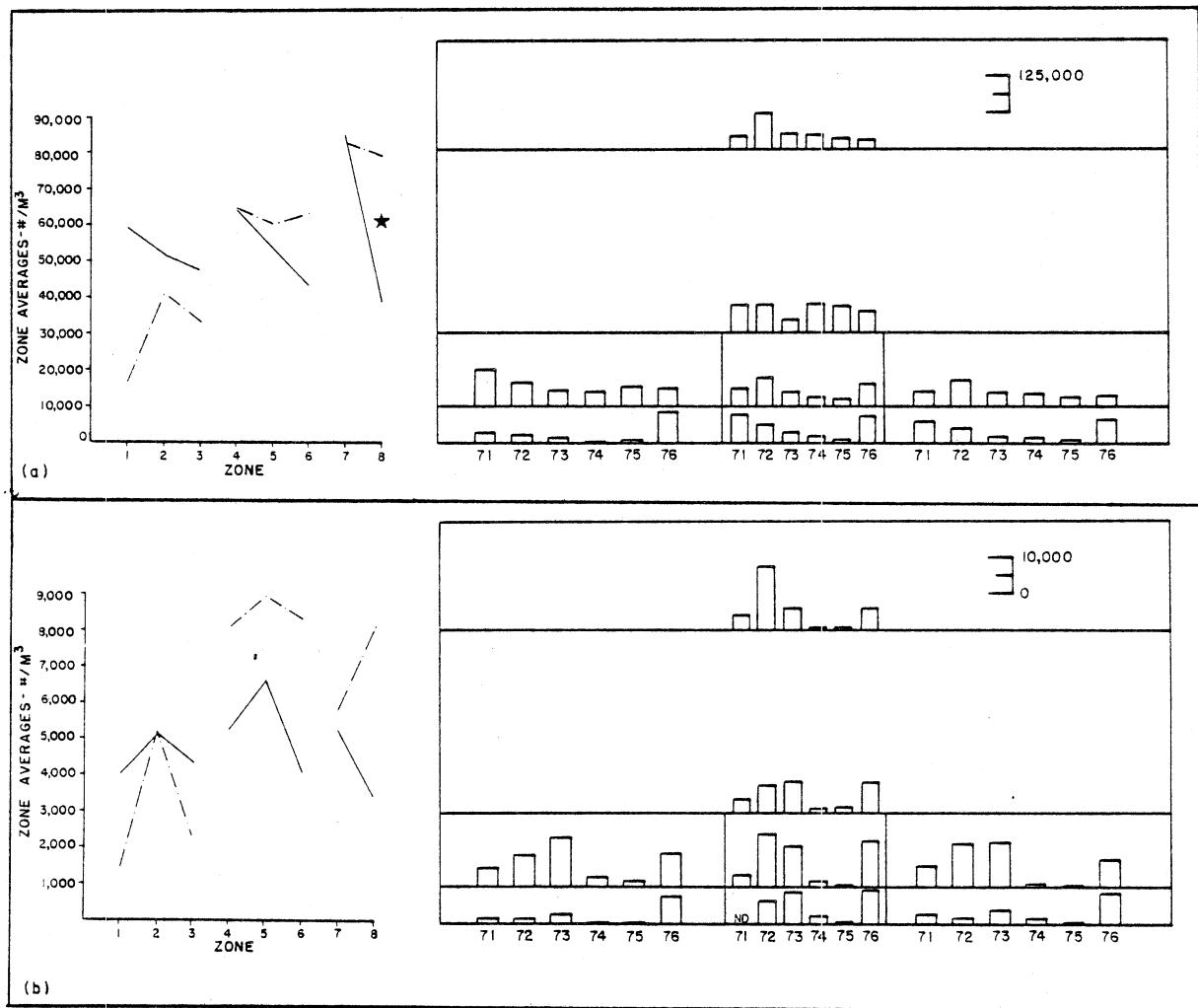


FIG. 38. The mean densities of zooplankton in July of each year, 1971-1976, and the mean preoperative and operative period densities plotted for each zone. Lines connect zones in the same depth grouping, inshore, middle, and inner and outer offshore zones. Stars indicate zones with significantly different preoperative and operative densities (Mann-Whitney U test =0.05). a) Total zooplankton, b) copepod nauplii.

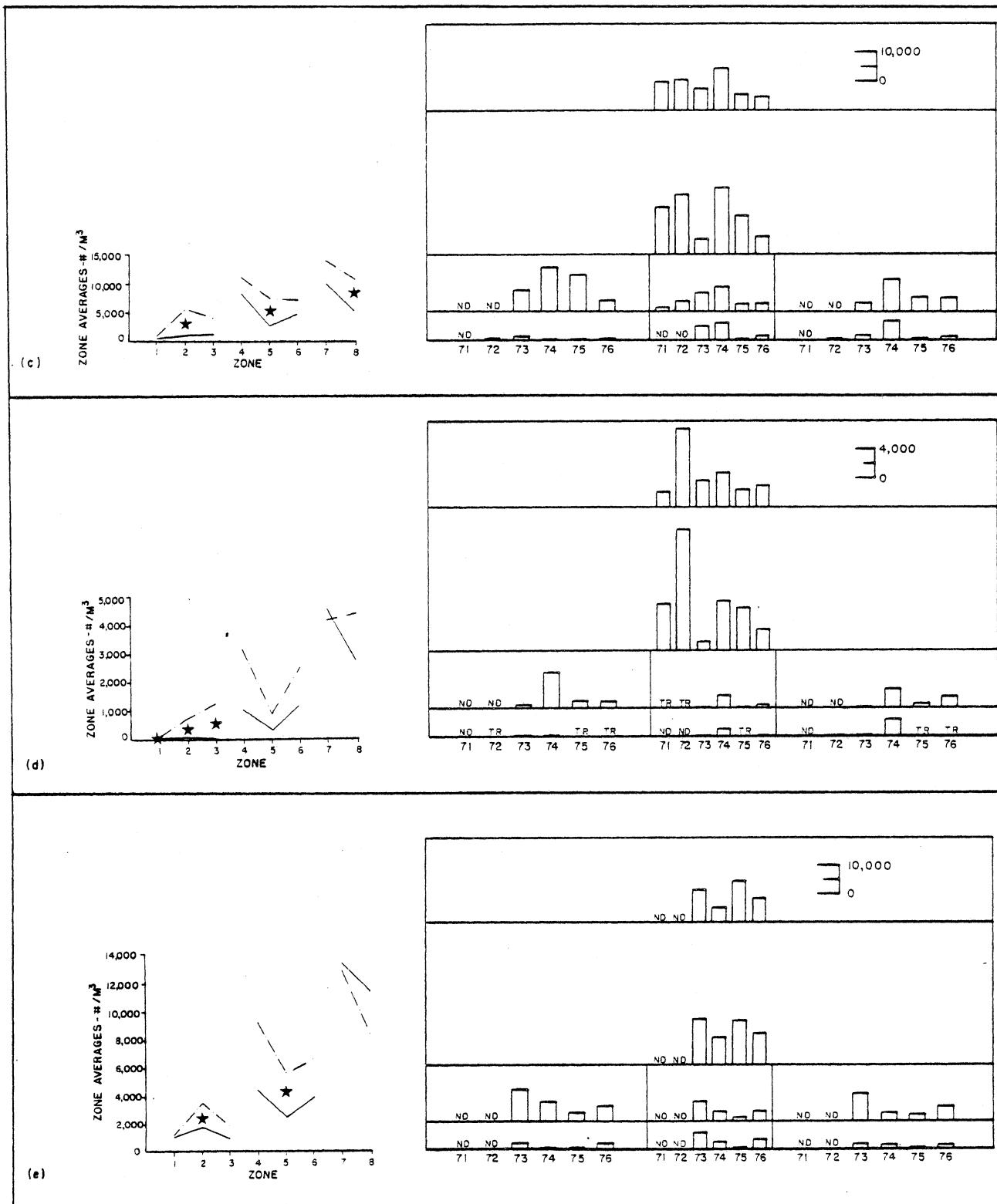


FIG. 38 continued. c) immature cyclopoids, d) adult Cyclops spp., e) immature Diaptomus spp.

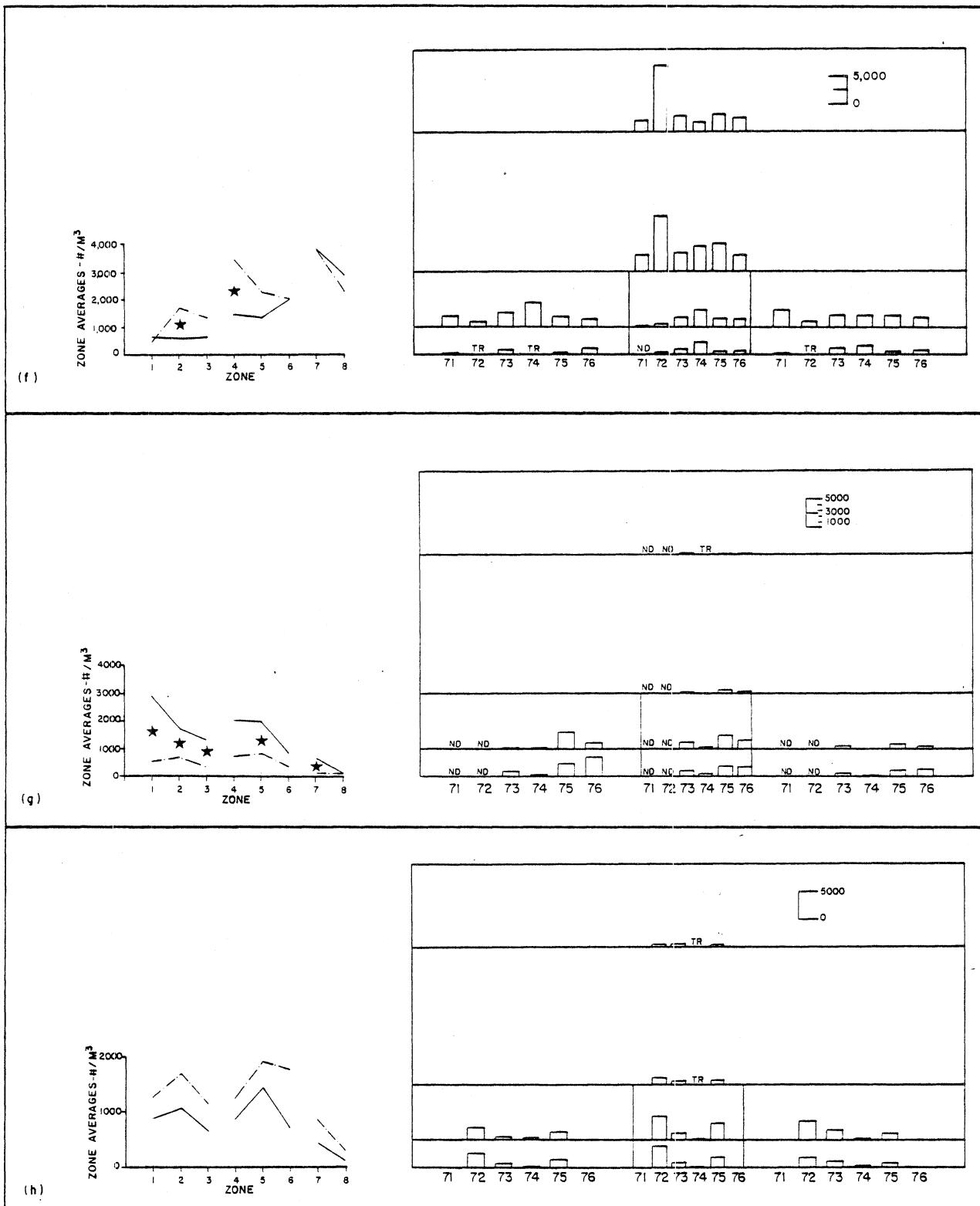


FIG. 38 continued. f) adult *Diaptomus* spp., g) *Eurytemora affinis*, h) *Asplanchna* spp.

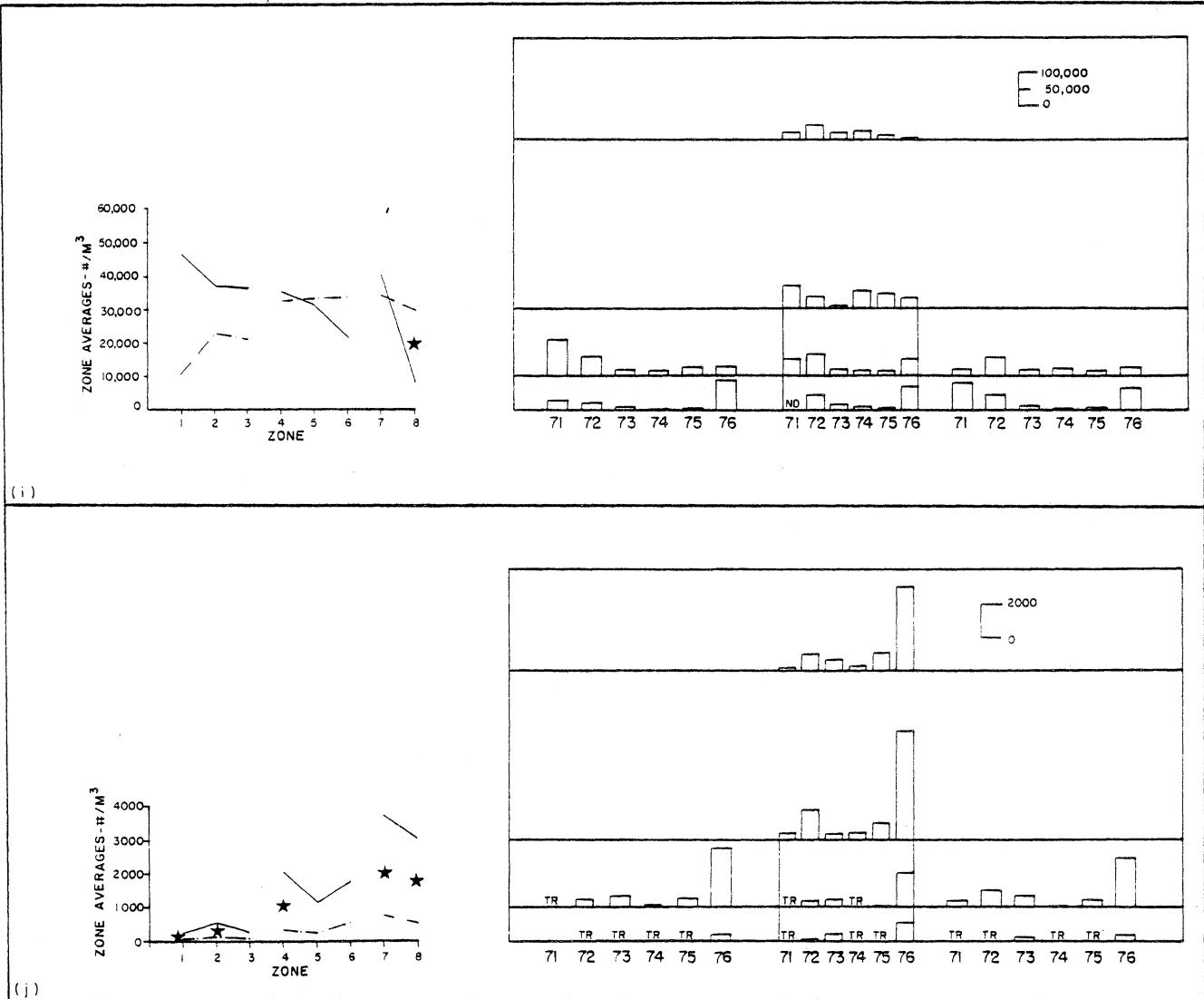


FIG. 38 continued. i) *Bosmina longirostris*, j) *Daphnia* spp.

TABLE 10. Results of the Mann-Whitney U test comparing October preoperational and operational densities of twelve zooplankton taxa in each of seven zones. The preoperational period is 1971-74 or a subset ending in 1974, and the operational period is 1975-76. Stations in zone 8 were not sampled in 1975 or 1976 (see text). Sample sizes are given in Appendix Table 45.

Taxon	Zone							Period
	1	2	3	4	5	6	7	
Order and Suborder Level								
Cladocerans	NS	NS	NS	*	NS	*	*	72-76
Copepod nauplii	NS	*	NS	*	*	*	*	72-76
Cyclopoids (C1-C6)	*	NS	NS	NS	NS	*	*	72-76
Calanoids (C1-C6)	*	NS	NS	NS	NS	NS	NS	72-76
<u>Genus, Species, Developmental Stage</u>								
<u>Bosmina longirostris</u>	NS	NS	NS	NS	NS	NS	*	72-76
<u>Eubosmina coregoni</u>	NS	NS	NS	*	*	*	*	72-76
<u>Daphnia</u> spp.	NS	*	*	NS	*	NS	NS	72-76
Cyclopoids (C1-C5)	*	NS	NS	NS	NS	NS	NS	73-76
<u>Cyclops</u> spp. C6	NS	*	*	NS	*	*	NS	73-76
<u>Diaptomus</u> spp. (C1-C5)	NS	*	*	NS	NS	NS	NS	73-76
<u>Diaptomus</u> spp. C6	NS	NS	NS	NS	*	NS	*	73-76
Total zooplankton	NS	NS	NS	NS	NS	*	NS	72-76

* significant difference, $\alpha = 0.05$

NS not significant

although differences were statistically significant only in zones 1, 6, and 7 (Table 10); no significant differences were detected in the plume zones. Immatures were less abundant (Fig. 39) in the preoperational period although differences were significant only in zone 1. Adults were of lesser numerical importance and occurred in reduced numbers (by a factor of 1.2 to 2); differences were not statistically significant in zones 1, 4, or 7.

Calanoid copepods occurred in similar concentrations in the preoperational and operational years (Table 10) except in zone 1 where these copepods were nearly twice as abundant in the operational period. Immatures (Fig. 39), the numerically dominant form, occurred in statistically similar concentrations over the survey grid although they were approximately 1.4 times more abundant in zones 2 and 3 in the preoperational period; these

differences were significant. Adult concentrations were greater in the southern inshore, the middle, and inner offshore regions in the operational period although these differences were significant only in zones 5 and 7. Only in the inshore plume zone were adult concentrations lower in the operational period. Nauplii were three times more abundant in the operational period and the differences were significant for all zones except 1 and 3.

DISCUSSION

Several years of preoperational and operational monitoring have revealed the complex variation in zooplankton population levels. Spatial and temporal variations were frequently large. Spatial patterns (inshore-offshore differences) were generally similar but the temporal patterns (timing and magnitude of population peaks) varied from year to year. The causes of these differences are not well understood and the validity of the measured differences is questionable, particularly when the data were collected at time intervals as large as one month. Sampling and subsampling variability, while comparatively small, also contribute to the overall variations in the estimate of zooplankton population size. All these sources of variation reduce the ability of our monitoring program to detect effects of power plant operation on the zooplankton community.

The preoperational and operational data were examined to evaluate the effects of power plant operation on 'the maintainance of a balanced indigenous population in the discharge area'. Measures of "balance" include succession patterns within the limits of natural, non-catastrophic conditions, diversity, self-perpetuation, and the non-dominance of pollution tolerant species (United States Environmental Protection Agency 1974). We defined the inshore plume zone (zone 2) as the discharge area in our studies. The middle plume zone (zone 5) which contained relatively small volumes of condenser-passed water and zooplankton was of secondary interest.

Zooplankton populations within the inshore plume zone exhibited many features of balance in 1975 and 1976. Succession patterns in these years were generally similar to patterns in the preoperational period. There was no evidence that typical summer taxa appeared earlier or persisted longer during the operational period than in the preoperational period. Most preoperational and operational differences in zooplankton succession patterns were associated with the magnitude of population size.

Statistical comparisons of zooplankton abundances in the inshore plume zone and, to a lesser extent, the middle plume zone, indicated that many taxa occurred in significantly different ($\alpha = .05$) concentrations between the preoperational and operational periods. Zone means generally differed by a factor of two or three between these periods. However, differences of similar magnitude were also observed in the control zones (although not as often statistically significant) suggesting that these differences were related to natural events. Differences in zooplankton abundances were also detected in the two offshore zones which were located well beyond any direct

impact of power plant operation.

Initially we were concerned with the observation that while preoperational and operational zone mean differences in the three inshore and in the three middle zones were similar in magnitude, differences were most often statistically significant in the two plume zones. The greatest number of significant differences were detected in the inshore plume zone. In addition, while the preoperational and operational zone means in the three inshore and the three middle zones were generally similar, the 95% confidence intervals for zone differences (Appendix, Tables 42-44) were larger in the control zones.

Two factors are primarily responsible for generating these results. These are the size of the zone and the number of stations in the zone. The inshore and middle plume zones (2 and 5) were comparatively small. They extended only 3 km alongshore in comparison to 8 km for the four control zones (1, 3, 4, and 6). Since zones 2 and 5 covered a smaller area, they were more likely to contain water masses of more uniform zooplankton composition than would be found in the larger zones.

Zone 2 contained 4 to 7 stations (7 since July 1974), and zone 5 contained 4 stations. The control zones contained 3 stations. Estimates of the zone means and variances are more accurate when they are based on a larger number of replicates (stations). Therefore, the design of our survey grid and analytical tests is biased with a greater sensitivity for detecting preoperational and operational differences in the plume zones than in the control zones.

At this point, with two years of operational data, there is no evidence that power plant operation has had an adverse effect on zooplankton populations in the discharge area. Zooplankton populations in zones 2 and 5 were generally similar to control populations upcurrent and downcurrent from the plume zone (Section 1). There was no evidence of localized losses or gains by any of the zooplankton taxa considered, although many taxa occurred in different preoperational and operational concentrations both in the plume zones and in the control zones (Section 2). Pollution tolerant taxa did not increase in the discharge area. While Eurytemora affinis was more abundant in zones 2 and 5 in July 1975 and 1976, it was also more abundant in the control zones. Limnocalanus macrurus, a cold water stenotherm, has not decreased in abundance in zones 2 and 5 since plant operation began. In fact, populations were particularly large both in the plume and control zones in April 1975. There was no apparent shift in the ratio of calanoid copepods to cyclopoid copepods and cladocerans; this ratio appears to decrease from cold, oligotrophic waters to warm, eutrophic waters (Patalas 1972). Rare copepods and cladocerans occurred in similar concentrations in the plankton in the preoperational and operational years. There was no evidence for a trend of increasing abundance of these taxa with continued plant operation although some differences in the numbers of epibenthic and benthic copepods

and cladocerans near the intake structures may have occurred (Section 4). No new species were observed in the plankton in 1975 or 1976.

Zooplankton populations in the inshore plume zone had the features of perpetuation in 1975 and 1976. Although we did not conduct field experiments to measure self-perpetuation, limited laboratory studies (Section 3) suggest that condenser-passed copepods were not reproductively impaired. Physical processes such as lake currents also replenish zooplankton populations in the plume zone. Currents move rapidly through the inshore plume zone, carrying water and zooplankton along the 3.2 km length of the zone in approximately 16 hours under average lake current velocities of 5.5 cm/sec (Ayers et al. 1967). By comparison, zooplankton generation times are in the order of days (rotifers, cladocerans), weeks (copepods) or even as long as one year for univoltine copepods such as Limnocalanus macrurus. Clearly, the physical movement of water is of greater importance in the perpetuation of zooplankton populations in zones 2 and 5 than reproductive activities.

Lake currents, by moving water and zooplankton rapidly through the plume area, reduce the thermal stresses experienced by plume-entrained zooplankton. Rapid mixing of condenser-passed water over the discharge jets cools the water, reducing stress. It is unlikely that short-term exposures (in the order of minutes) to water temperatures a few Centigrade degrees above ambient would have a measurable effect on zooplankton mortality. Condenser-passed zooplankton experienced more severe thermal and mechanical stresses. Such mortality losses were low (Section 3) and were not detectable in the lake against the background of natural variation. We conclude from these studies that power plant operation in 1975 and 1976 had no detectable effect on the maintenance of a balanced indigenous population in the discharge area.

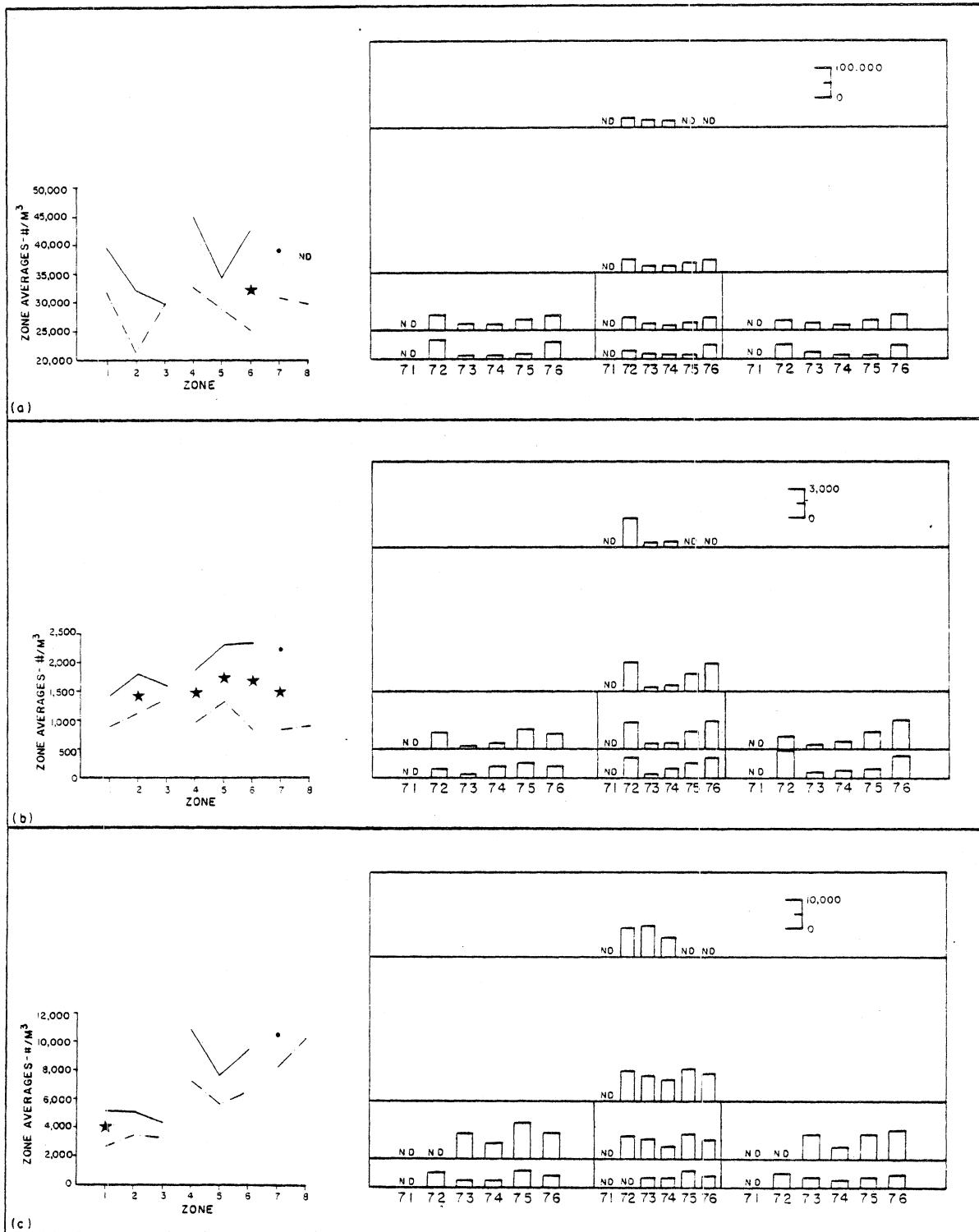


FIG. 39. The mean densities of zooplankton in October of each year, 1971-1976, and the mean preoperational and operative period densities plotted for each zone. Lines connect zones in the same depth grouping, inshore, middle, and inner and outer offshore zones. Stars indicate zones with significantly different preoperative and operative densities (Mann-Whitney U test $\alpha = 0.05$). a) Total zooplankton, b) copepod nauplii, c) immature cyclopoids.

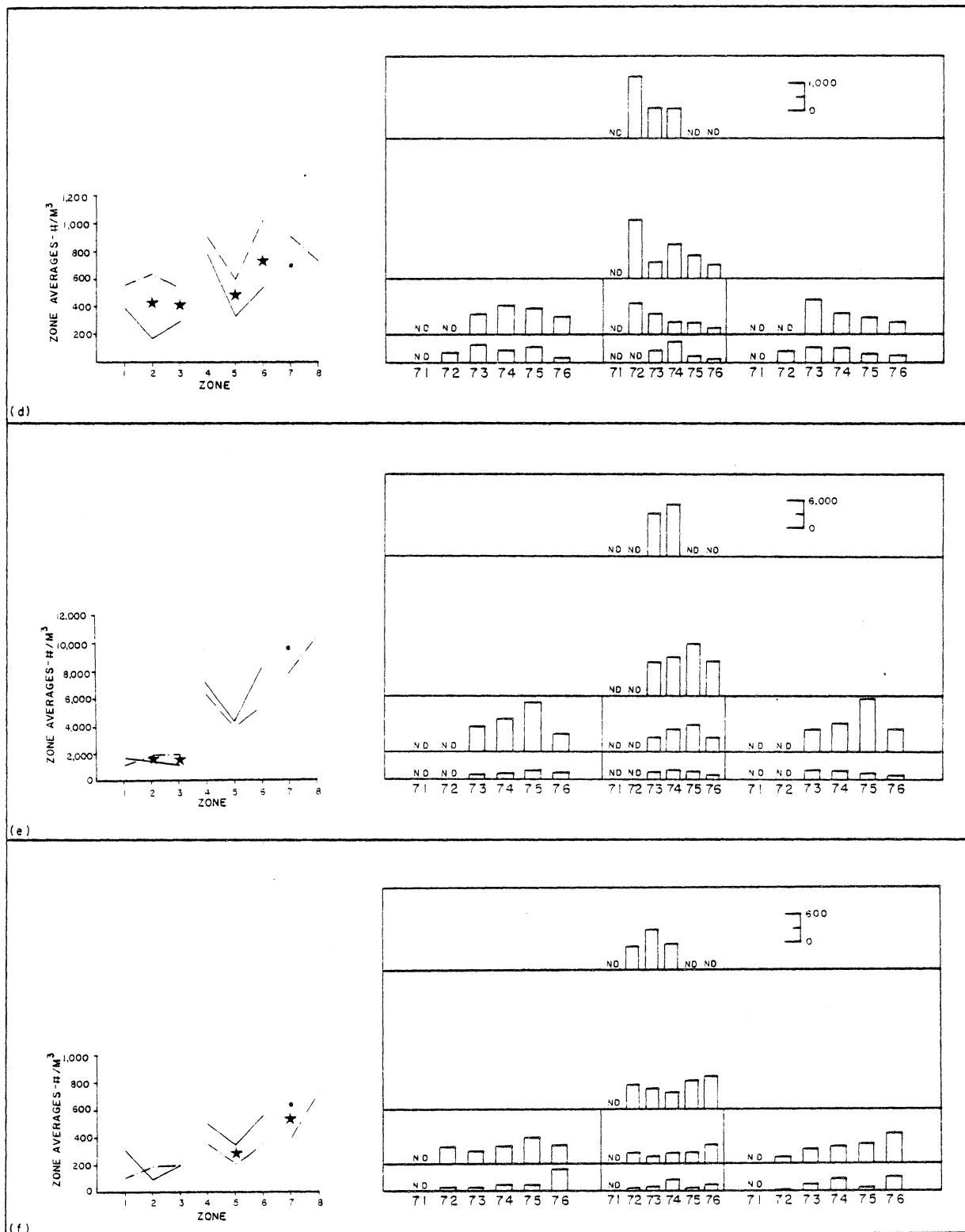


FIG. 39 continued. d) adult Cyclops spp., e) immature Diaptomus spp., f) adult Diaptomus spp.,

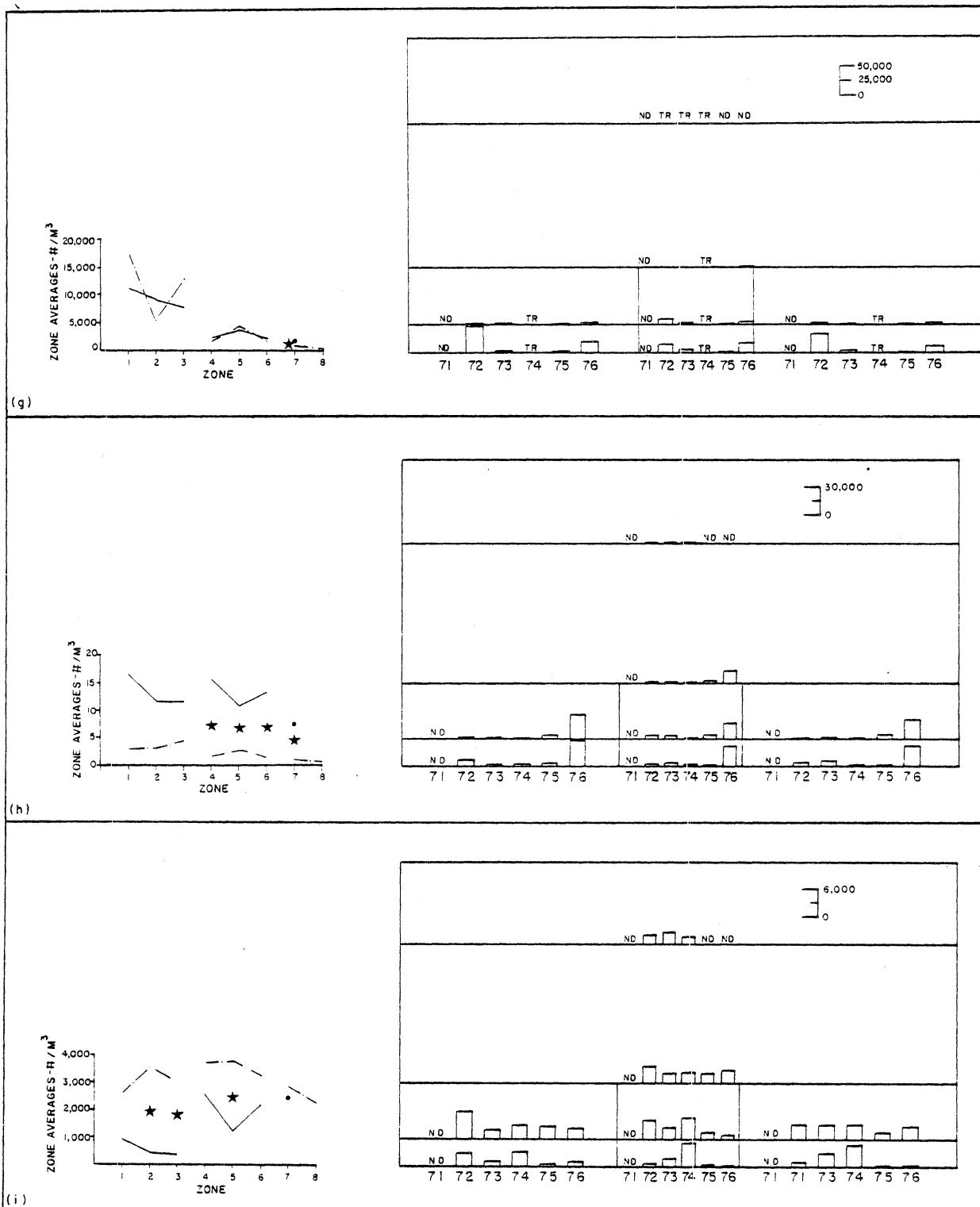


FIG. 39 continued. g) Bosmina longirostris, h) Eubosmina coregonis and i) Daphnia spp.

SECTION 3

THE EFFECTS OF PLANT PASSAGE

INTRODUCTION

In the previous section, we stated that numerical losses of zooplankton following condenser passage were not detectable in the inshore plume zone. Additional studies were conducted within the plant to estimate zooplankton mortality in condenser-passed water before discharge into the lake. Numerical losses were estimated both immediately after plant passage (0-hour) and after periods of 6 and 24 hours. Immediate losses were of the most interest since they would be concentrated within the thermal plume. Subsequent losses of zooplankton (6 and 24 hours after plant passage) were of secondary interest. Under average lake conditions (mean current speed 5.5 cm/sec, Ayers et al. 1967), these additional dead zooplankton would be transported beyond the inshore plume zone.

MATERIALS AND METHODS

Mortality Studies

The mortality studies were conducted once a month, twelve months a year. Samples were collected from the intake and discharge forebays (Fig. 40) with the Zaggot Trap (Fig. 41), a modification of the sampler designed by Icanberry and Richardson (1973). The sampler was first primed with water drawn by a Hale diaphragm pump. A carrier fitted with a $158\ \mu$ aperture net was lowered into the chamber to filter the water. The lid was clamped down and hose connections were arranged so that water was drawn from the intake forebay through a fixed pipe to the sampler, and then through the pump. Collection times varied from one to two minutes depending on the concentration of zooplankton in the water. Approximately 40 gallons (0.2 m³) of water were filtered each minute.

Simultaneous samples were collected in the intake forebay (Fig. 40) at grate location MTR 1-5 (5 m below the water surface) and from the discharge forebay of Unit 1. Access was limited to a single location in the discharge bay. Rigid pipes, 7.6 cm in diameter, were mounted in the forebays and flexible 7.6 cm diameter hoses connected the pipe to the sampler. The first series of samples was collected within a half an hour of sunrise. The second series was collected approximately one hour later (after the first series had been processed).

After sample collection, the mesh carrier was removed from the sampler, the outside washed down with water, and the contents of the plankton bucket transferred to a clean, formalin-free jar. The two samples were then taken to an on-site laboratory where each was subdivided as many times as necessary in a Folsom plankton splitter to give six subsamples, each containing several hundred zooplankton. Two subsamples were immediately examined (0-hour), and

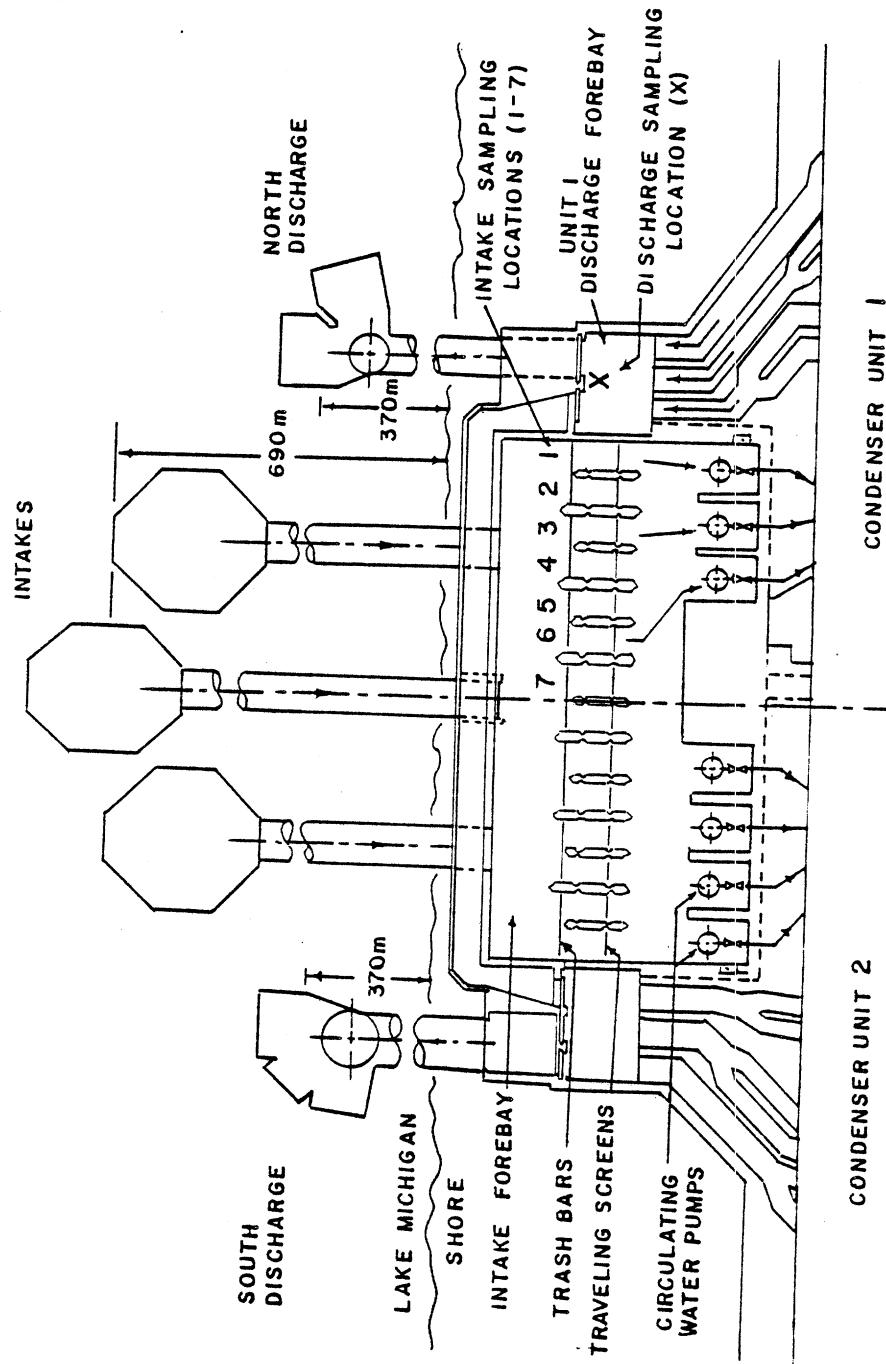


FIG. 40. A schematic view of the condenser cooling-water system of the Cook Nuclear Plant.

LABELS - TUB

- 1 - Intake
- 2 - 3" Quick Release Hose Fitting
- 3 - Lid Clamp
- 4 - Lid
- 5 - Mesh Carrier
- 6 - Mesh
- 7 - Plankton Bucket
- 8 - 3" Quick Release Hose Fitting
- 9 - Discharge
- 10 - Pump

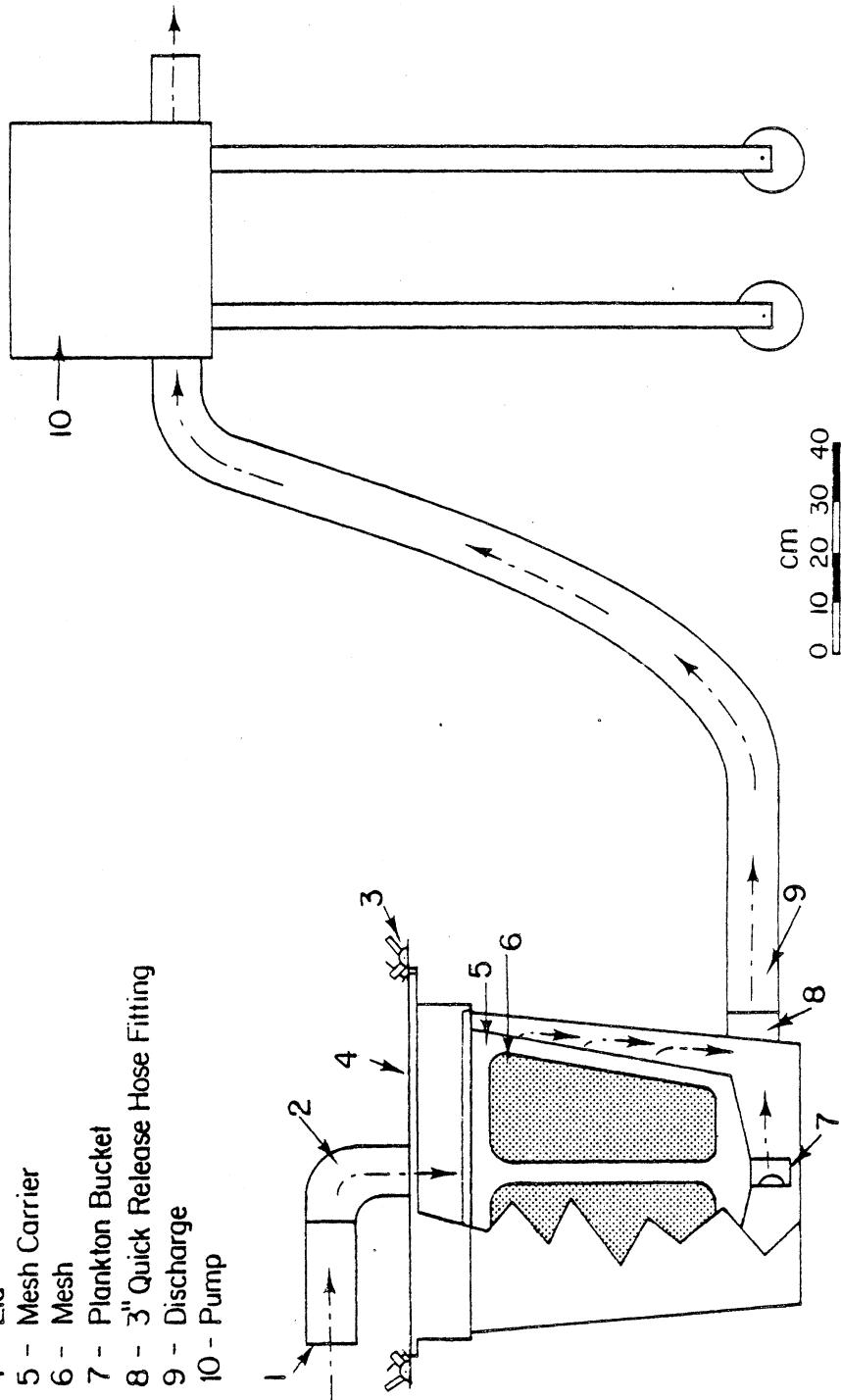


FIG. 41. Schematic view of the live zooplankton sampler (Zaggot Trap) and water flow through the trap and pump system.

the remaining four were placed in one liter beakers containing 750 ml of filtered (158 μ) intake water, and maintained at ambient lake water temperatures in a Freas 850 incubator. All incubations were done in the dark. Two subsamples from each location were examined 6 hours later and the remaining two were examined 24 hours later.

Each sample was examined in a circular counting dish under a Bausch and Lomb stereozoom microscope. Organisms which exhibited no visceral or appendicular movements even after gentle prodding were classified as 'dead'. Organisms were identified to suborder (nauplii), genus (Asplanchna spp. immature copepodites), or species (adult copepods, cladocerans). Dead organisms were placed in a separate vial and preserved with Koechie's fluid. After complete examination of the sample, the remaining live zooplankton were preserved for later examination. The percentage of dead zooplankton in the intake and discharge samples was then calculated (Appendix Tables 45-90).

Long-Term Incubation Studies

In order to examine long-term (days) effects of plant passage, live zooplankton from the intake and discharge waters were brought back to Ann Arbor and used in a series of culturing trials. Healthy Cyclops spp. and Diaptomus spp. cultures consisting of two replicates of approximately 25 animals each were set up for each location in October and November 1975 and January and February 1976. Animals were placed in 250 ml beakers and maintained within 1 or 2 $^{\circ}$ C of ambient water temperatures at the time of sample collection. A few milliliters of food culture (Robertson et al. 1974) were provided weekly. Initially cultures were examined at least once a week, organisms counted, dead zooplankton removed, and the culture water (0.45 μ millipore-filtered lake water) changed. After several weeks, the cultures were examined less frequently. Notations were made of the presence of nauplii and ovigerous females. After March 18, 1976 when experience was gained in identifying moving zooplankton, immature copepodites were distinguished from adults.

Heterogeneity Studies

A heterogeneity study was conducted in the intake forebay to determine if zooplankton mortality varied with grate location and/or depth. Since we collect samples from only one location in the intake forebay to estimate intake mortality, the degree to which this one location is representative of the average percent of dead zooplankton had to be determined. In a previous study (Evans 1975), differences in zooplankton concentrations between several locations in the intake forebay were detected. Some of these differences may have been due to large numbers of dead zooplankton accumulating in eddies or at particular depths in the intake forebay. Since this would have severely biased the results of our mortality investigations, a study was conducted between May 28 and 30, 1975 to examine spatial variability in zooplankton mortality within the intake forebay.

This was done by sampling at three different locations in the intake forebay. Simultaneous two-minute samples were collected at grate locations MTR 1-1, 1-3, and 1-5 from a depth of 5m. Four samples were collected on May 28 and an additional two the following morning to give a total of six samples (12

subsamples) from each location. Mortality differences with respect to depth were examined at grate MTR 1-5 by sampling at depths of 0.6, 5.5, and 8.5 m below the water surface. A total of two samples were collected on May 29 and an additional two the following day to give a total of four samples (eight subsamples) from each depth.

RESULTS

Heterogeneity Studies

Zooplankton mortality was lowest at grate MTR 1-5 and highest at MTR 1-3 (Table 11). These differences were not significant at the 0.95 confidence level (Kruskall-Wallace Distribution Free Analysis of Variance). Similarly, zooplankton mortalities were higher at 8.5 m than at the other depths (Table 12) but these differences were not statistically significant. Therefore a depth of 5 m at grate location MTR 1-5 appears to be a representative sampling location in the intake forebay for mortality estimates within the precision of existing measurements.

General Features of the 23-Month Mortality Study

Intake-water temperatures during the 2-year study varied from 1°C to over 23°C while discharge water temperatures were generally 10°C higher (Fig. 42). In the summer, discharge water temperatures approached but did not exceed 35°C, the temperature suggested by several studies as approaching the upper lethal limit for short-term exposures to elevated temperatures. The plant pumped water at a rate varying from 0.6 to 0.8×10^6 gpm (2.8×10^3 m³/min) during most of the sampling period. Lower rates (and lower velocities) were utilized during the winter and higher rates during the summer. The plant recirculated water in February and March 1975, discharging heated water directly into the intake forebay.

Nauplii mortalities (Fig. 43) were similar between the intake and discharge bays in most months although there was a slight trend for a greater difference in mortality between the two locations to occur during the summer and autumn months. There was no evidence of increased mortality in the discharge waters with increasing water temperature.

Immature Cyclops spp., adult Cyclops spp., immature Diaptomus spp., and adult Diaptomus spp. (Fig. 43) mortalities tended to be highest during recirculation (February and March 1975) and during storm activity (January 1976). Immature copepodites also tended to exhibit greater differences in intake and discharge mortalities during the warmer summer and autumn months.

Bosmina longirostris, Eubosmina coregoni, and Daphnia spp. (Fig. 43) exhibited no seasonal pattern in differential mortality. Similar mortalities were observed in the intake and discharge waters.

General features of the 23-month mortality study include:

TABLE 11. Percentage zooplankton mortality at three intake forebay locations on May 28-29, 1975.

Sample Number	Grate 1-1 percentage mortality	Grate 1-3 percentage mortality	Grate 1-5 percentage mortality
1	0.3	0.6	1.0
2	1.7	2.0	1.0
3	2.7	4.2	1.5
4	0.4	3.2	1.0
5	6.2	12.6	0.8
6	1.3	2.0	2.3
AVG.	2.1	4.1	1.3

TABLE 12. Percentage zooplankton mortalities at three depths on May 29-30, 1975. All samples were collected at intake forebay grate 1-5.

Sample Number	0.6 m	5.5 m	8.5 m
1	4.0	1.4	4.9
2	1.7	1.4	2.5
3	3.9	6.9	7.2
4	2.4	1.8	1.4
AVG.	3.0	2.9	4.0

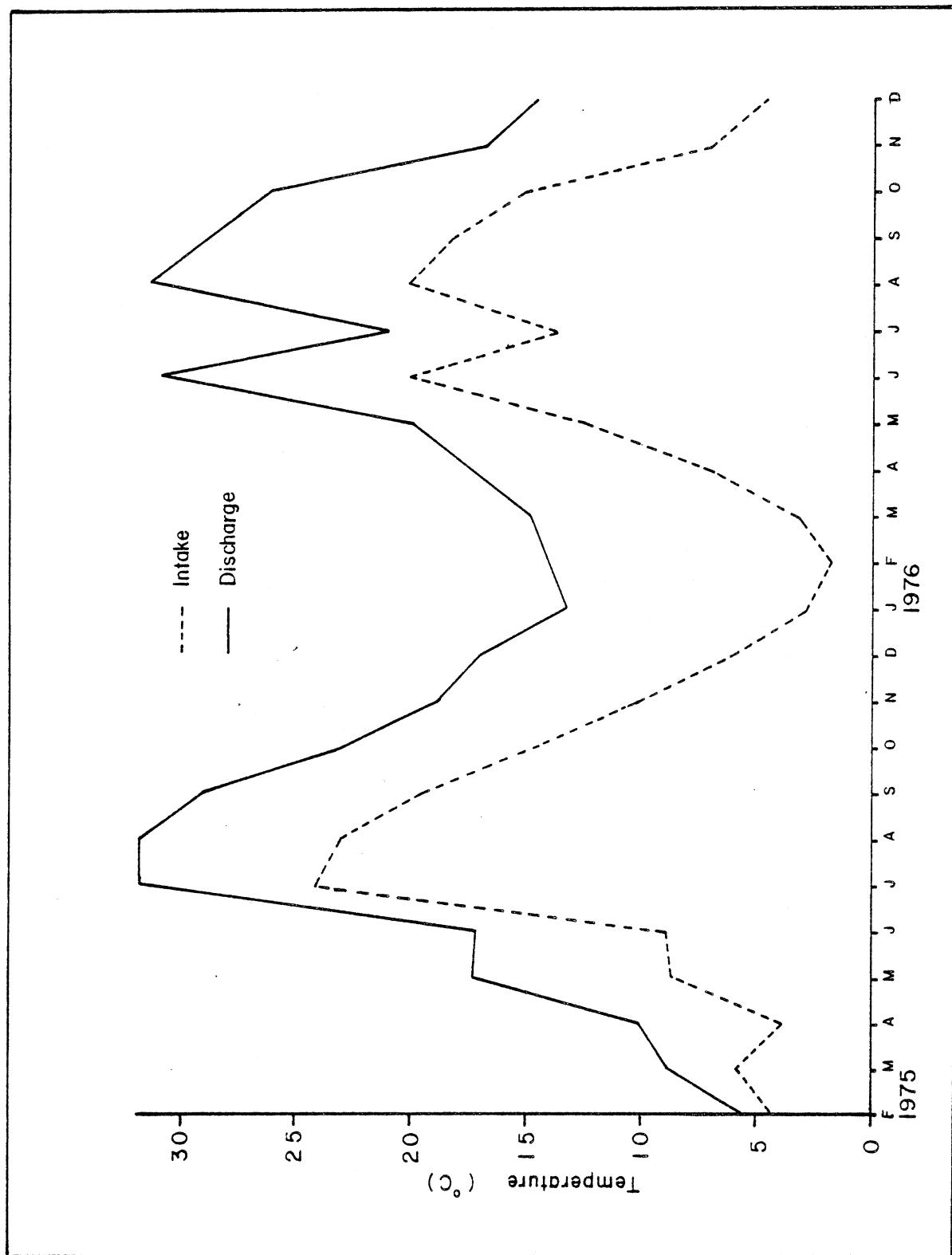


FIG. 42. Intake and discharge water temperatures, 1975-76.

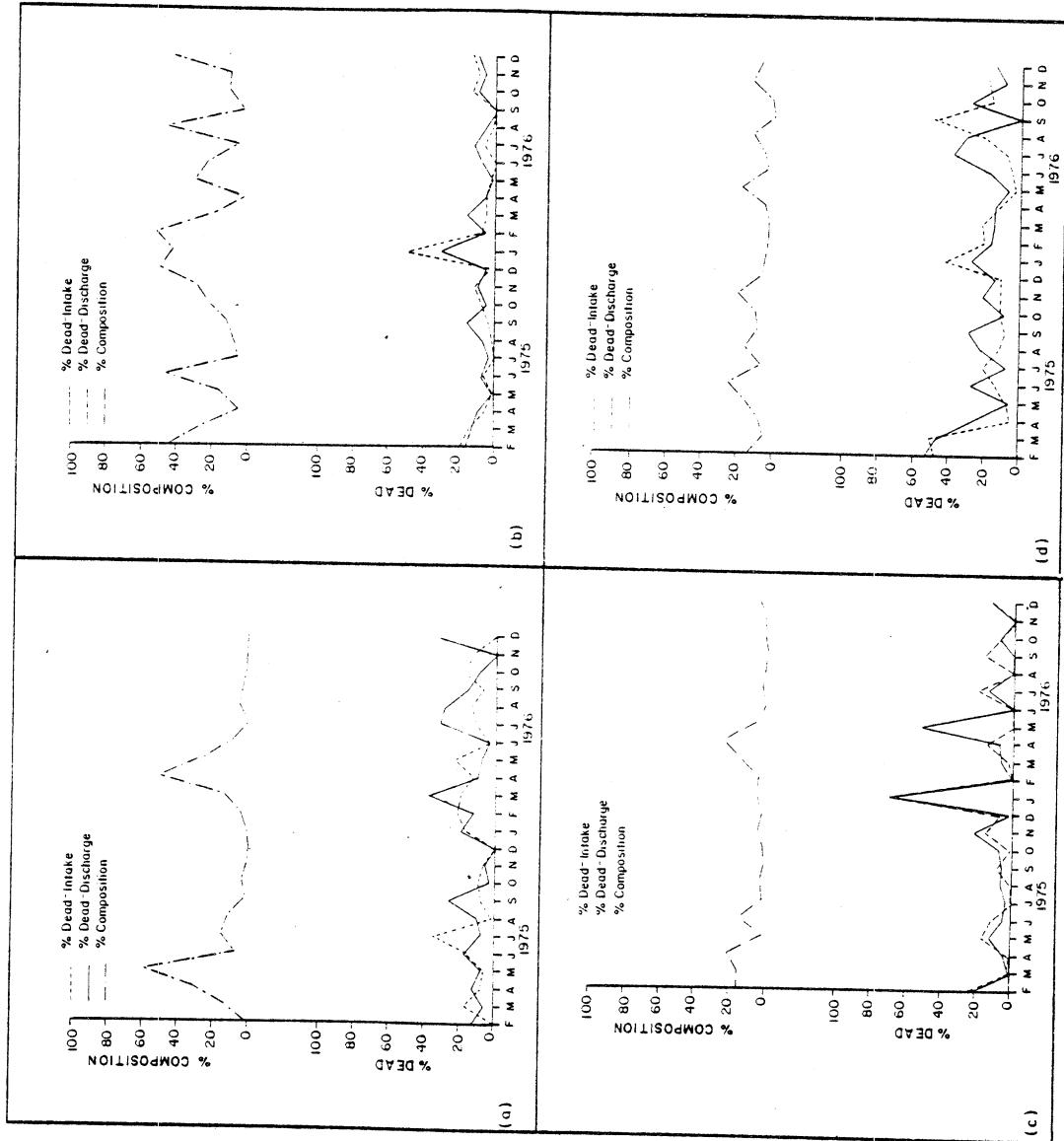


FIG. 43. Monthly mean mortalities (0-hour) for several zooplankton taxa and the mean proportion of total zooplankton (%) accounted for by each taxa. a) Copepod nauplii, b) Cyclops spp. C1-C5, c) Cyclops spp. C6, d) Diaptomus spp. C1-C5.

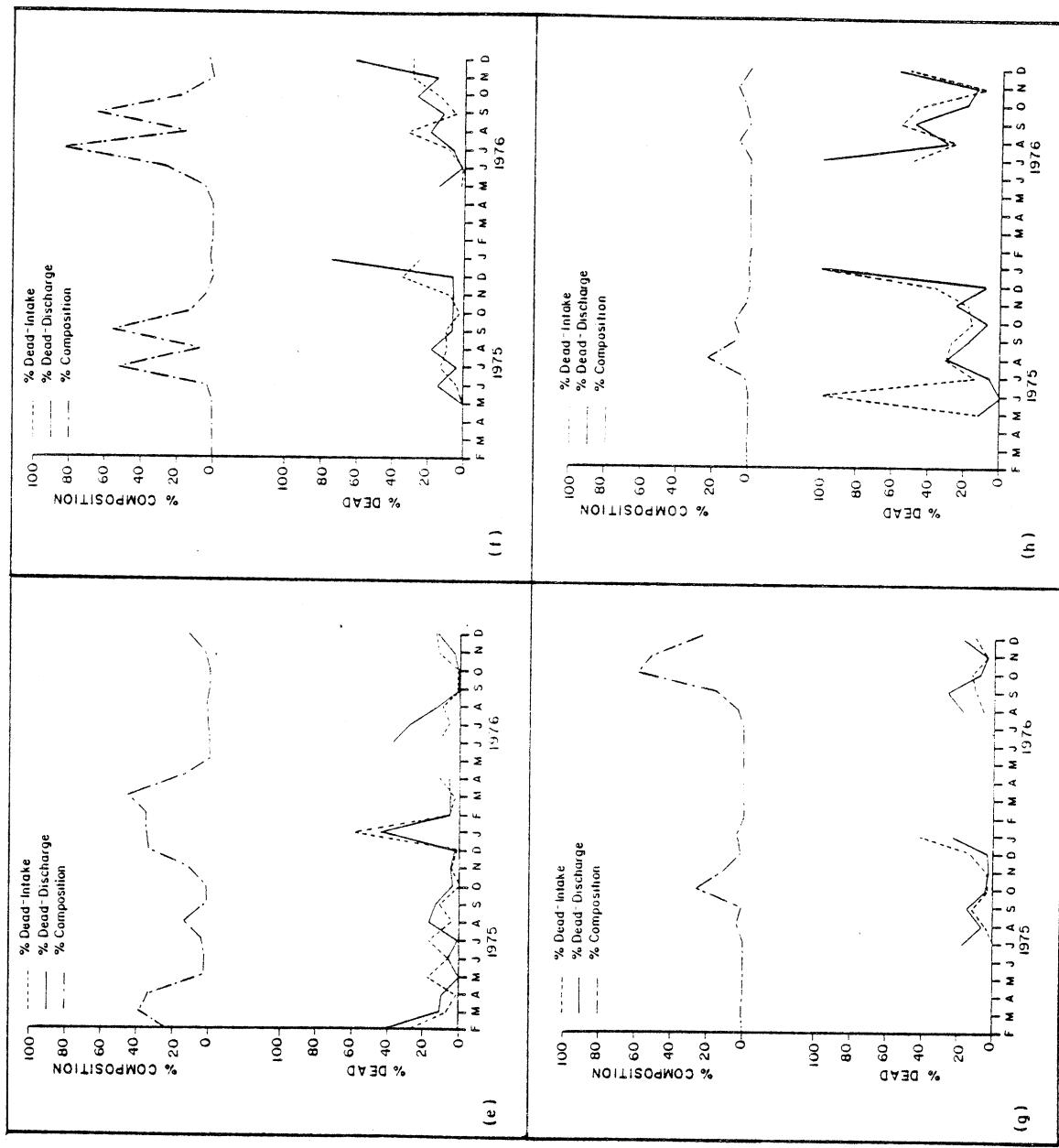


FIG. 43 continued. e) *Diaptomus* spp. f) *Bosmina longirostris* g) *Eubosmina coregoni*, and h) *Daphnia* spp.

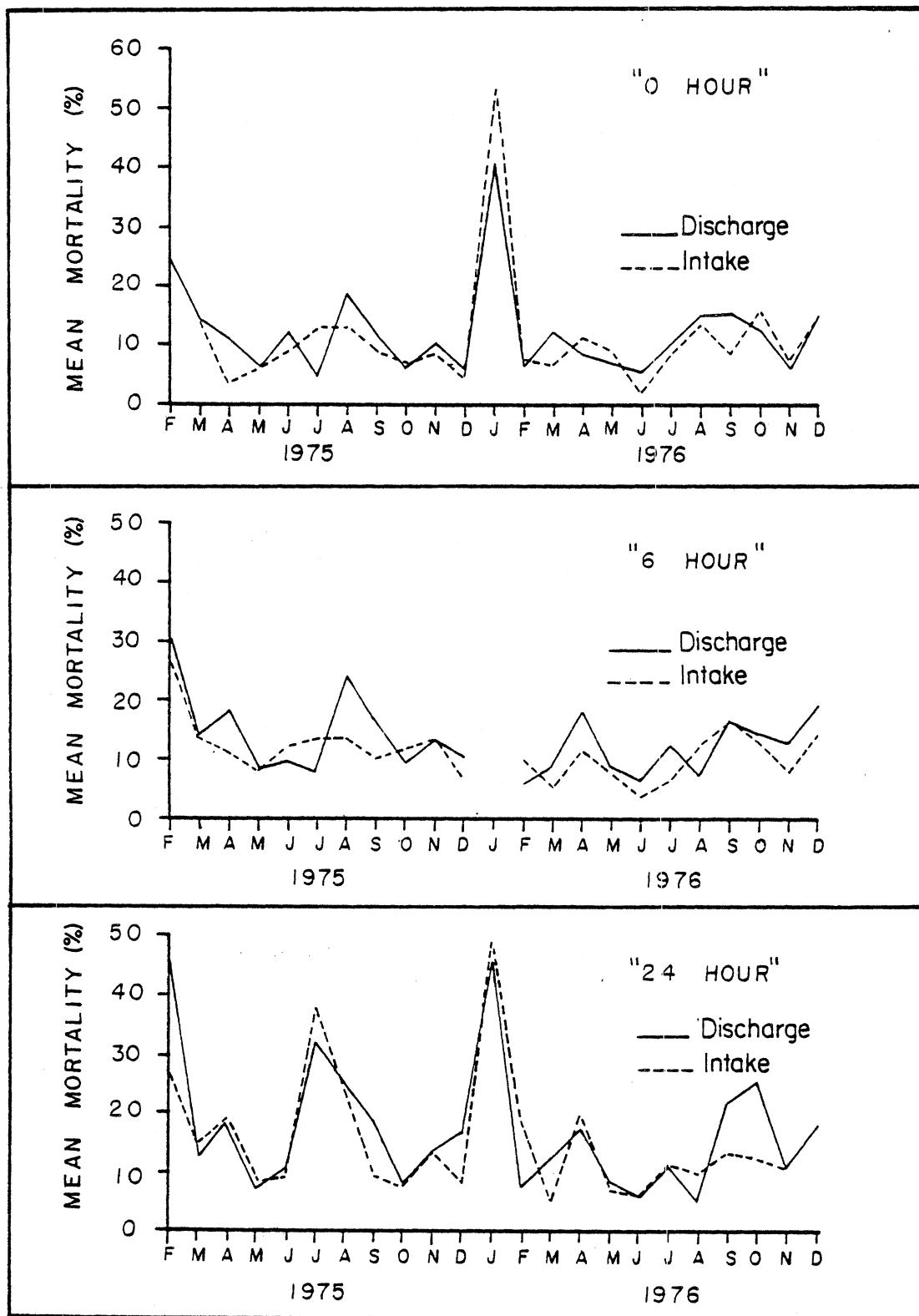


FIG. 44. Monthly mean mortality of total zooplankton at each incubation time.

(i) Total zooplankton mortalities ranged from 2 to 50% in the intake waters and from 5 to 40% in the discharge bay (Fig. 44) at 0-hours. The operating characteristics of the power plant (recirculation), lake conditions (storms), and variations in zooplankton taxa composition and their mortalities produced this variation.

(ii) Only small differences in zooplankton mortalities existed between the intake and discharge waters with the 0-hour mortality for total zooplankton averaging 11.8% and 12.0% respectively.

(iii) There was a wide range in the mean intake and discharge mortalities for the 29 most commonly collected taxa. Mortalities for some taxa including Daphnia retrocurva, Holopedium gibberum, and Diaphanosoma leuchtenbergianum were high, exceeding 19% in both the intake and discharge waters (Table 13). Other taxa such as immature Cyclops spp. copepodites and Asplanchna spp. tended to have lower mortalities. Taxa with high mortalities in the intake samples frequently were physically damaged and mortalities probably were incurred during collection. Mortalities were similarly high in the discharge samples.

(iv) Zooplankton mortalities tended to increase with incubation time both in the intake and discharge samples (Table 13). The mean 23-month mortality of total zooplankton after 24 hours incubation was 15.7% in the intake series and 16.2% in the discharge series (Fig. 44). The similar increases both in the intake and discharge samples suggest that there were no delayed effects due to condenser passage.

Results of the long-term culturing experiment also failed to show any delayed effects of condenser passage. Diaptomus spp. and Cyclops spp. cultures were maintained for periods of up to several weeks (Figs. 45-47) and mortality rates were similar both in the intake and discharge series. Females produced viable eggs in both intake and discharge cultures. In some experiments, development proceeded to the early copepodite stages (Fig. 47). Cyclops spp. cultures were easier to maintain and persisted for a longer period of time than the Diaptomus spp. cultures.

Statistical Analyses of the Mortality Data by Taxa and Incubation Time

Statistical analyses were performed to determine whether or not zooplankton mortalities were significantly higher in the discharge waters than in the intake waters. Analyses were performed for all the taxa shown on Table 13 and for major zooplankton categories including adult Cyclops spp. and Diaptomus spp., immature (C1-C5) and adult (C6) calanoid and cyclopoid copepods, and cladocerans.

The mortality data did not meet the assumptions of a parametric statistical model. The monthly variances were not homogeneous, invalidating the use of a 2-way parametric analysis of variance (with month and location effects). A chi-square test was not appropriate since the data contained

TABLE 13. The mean mortalities over 23 months (February 1975 through December 1976) for 28 taxa, the number of samples (N) in which the taxa were found, and the mean percentage total zooplankton (for N samples) accounted for by each taxon.

Taxon	0 Hr				6 Hr				24 Hr				% Composition
	Intake X	Intake N	Discharge X	Discharge N	Intake X	Intake N	Discharge X	Discharge N	Intake X	Intake N	Discharge X	Discharge N	
Copepod nauplii	12.4	47	13.6	48	11.3	45	16.5	45	14.8	47	14.6	47	11.0
<i>Cyclops</i> spp. C1-C5	8.4	48	9.1	48	7.8	45	11.4	45	8.5	47	10.8	47	23.5
<i>Cyclops bicuspidatus thomasi</i> C6	9.5	45	11.9	45	11.0	43	12.7	42	13.4	44	19.9	44	6.9
<i>Cyclops vernalis</i> C6	1.2	14	0.7	15	3.8	13	0.0	15	20.3	15	16.4	19	0.7
<i>Tropocyclops</i> C1-C5	19.3	19	15.0	16	3.3	15	31.4	15	10.1	12	2.2	15	0.5
<i>Propoecyclops prasinus mexicanus</i>	9.1	31	9.8	35	12.7	29	13.1	27	14.3	30	10.5	31	3.6
<i>Diaptomus</i> spp. C1-C5	19.0	48	22.2	47	20.3	45	26.8	45	28.0	47	28.1	47	9.3
<i>Diaptomus ashlandi</i> C6	15.4	37	12.0	36	10.3	32	10.6	34	15.4	35	20.3	36	10.3
<i>Diaptomus minutus</i> C6	5.1	40	14.1	40	11.0	34	17.6	34	20.7	38	20.1	37	3.0
<i>Diaptomus oregonensis</i> C6	10.8	33	13.1	37	6.8	27	11.5	27	8.5	31	19.0	34	4.2
<i>Diaptomus sictilis</i> C6	18.2	22	18.5	23	15.0	17	10.7	20	12.7	20	22.9	19	3.5
<i>Epischura</i> C1-C5	38.4	16	25.3	15	12.9	11	28.5	17	31.5	14	39.0	15	0.8
<i>Epischura lacustris</i> C6	50.0	6	12.5	8	42.9	7	44.4	9	0.0	5	26.7	5	0.1
<i>Baryteniora</i> C1-C5	6.3	25	8.4	26	5.4	25	9.4	24	17.1	25	19.0	26	3.6
<i>Baryteniora affinis</i> C6	9.2	19	1.3	19	6.3	16	11.1	18	26.4	22	9.7	18	0.6
<i>Limnozoalanus</i> C1-C5	14.8	7	29.2	9	36.6	6	30.7	5	26.6	8	1.9	7	1.8
<i>Limnoecitanus macrurus</i> C6	12.8	11	11.6	9	21.4	10	15.2	10	4.5	8	5.0	10	2.0
<i>Bosmina longirostris</i>	12.5	38	19.3	39	15.7	34	13.3	35	15.6	37	10.5	37	19.5
<i>Ceriodaphnia quadrangula</i>	0.0	4	6.7	4	3.3	5	5.0	5	5.0	5	0.0	5	0.5
<i>Chydorus sphaericus</i>	7.6	12	0.0	14	1.3	15	2.8	18	16.1	17	7.4	16	0.6
<i>Daphnia galeata mendotae</i>	17.9	21	26.5	19	28.9	20	28.0	19	21.6	19	19.2	18	1.0
<i>Daphnia retrocurva</i>	30.8	26	34.6	27	33.7	22	33.9	24	34.3	23	32.1	24	4.5
<i>Diaphanosoma leuchtenbergianum</i>	44.3	16	47.1	16	66.1	17	60.7	12	70.7	13	67.0	16	0.6
<i>Eubosmina coregoni</i>	8.6	25	17.4	30	16.8	26	10.1	27	15.5	25	21.8	27	16.0
<i>HoLopedium gibberum</i>	44.3	14	21.2	11	48.3	10	48.1	9	61.6	7	77.6	7	0.5
<i>Leptodora kindtii</i>	23.1	13	27.9	12	78.6	12	71.5	13	80.0	10	82.4	9	0.3
<i>Polyphemus pediculus</i>	25.0	4	16.6	7	25.0	4	25.0	5	28.6	7	10.0	6	0.3
<i>Asplanchna</i> spp.	5.3	30	2.9	26	5.7	21	11.7	21	14.2	24	14.5	22	2.7
Total Zooplankton	11.8	48	12.0	48	11.3	45	13.1	45	15.7	47	16.2	47	

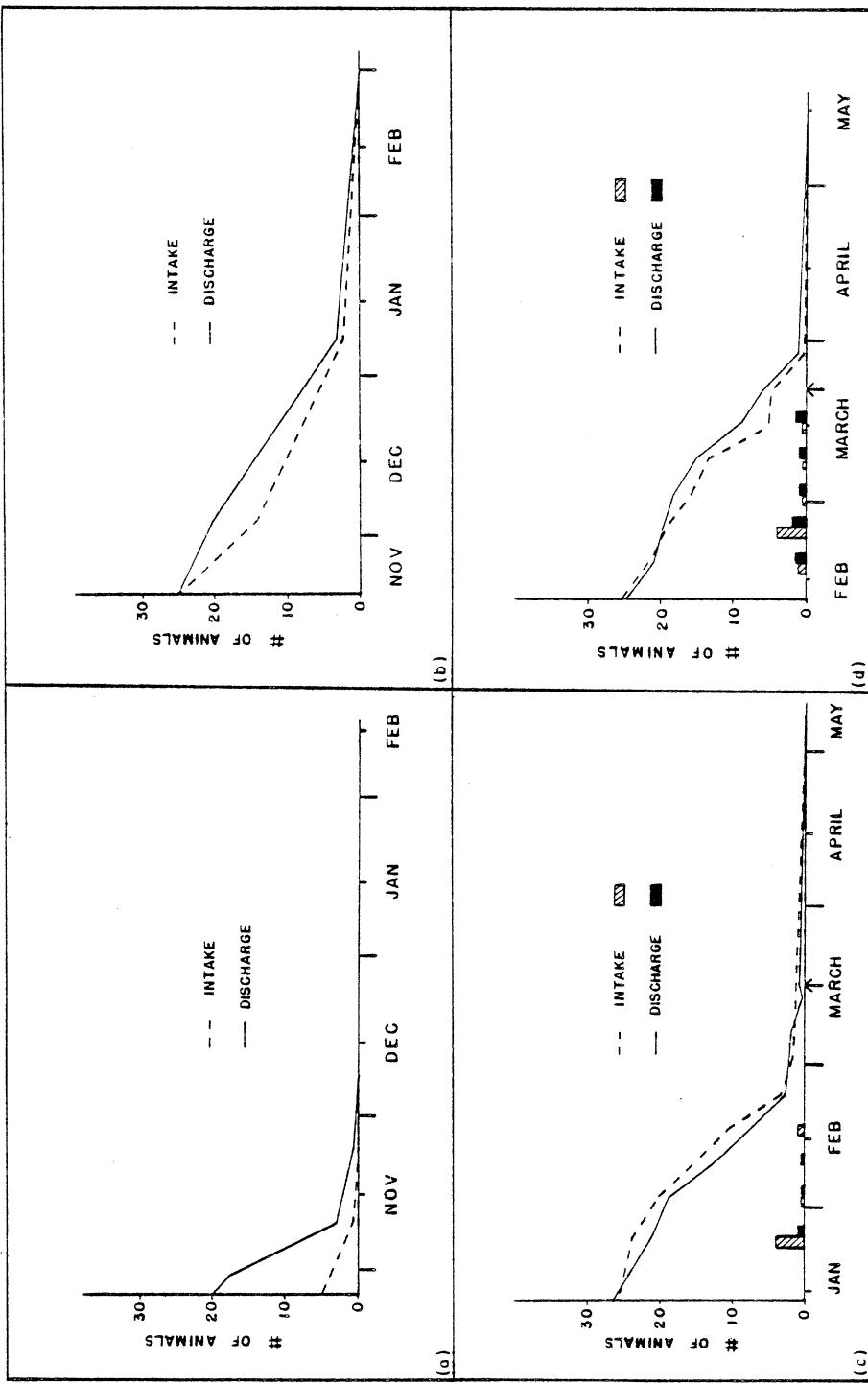


FIG. 45. The survival of adult *Diaptomus* spp. in cultures of these organisms collected from the intake and discharge waters on a) 17 October 1975, b) 20 November 1975, c) 14 January 1976 and d) 11 February 1976. Histograms refer to the number of ovigerous females. After March 18 (↑) early copepodites were included with nauplii counts.

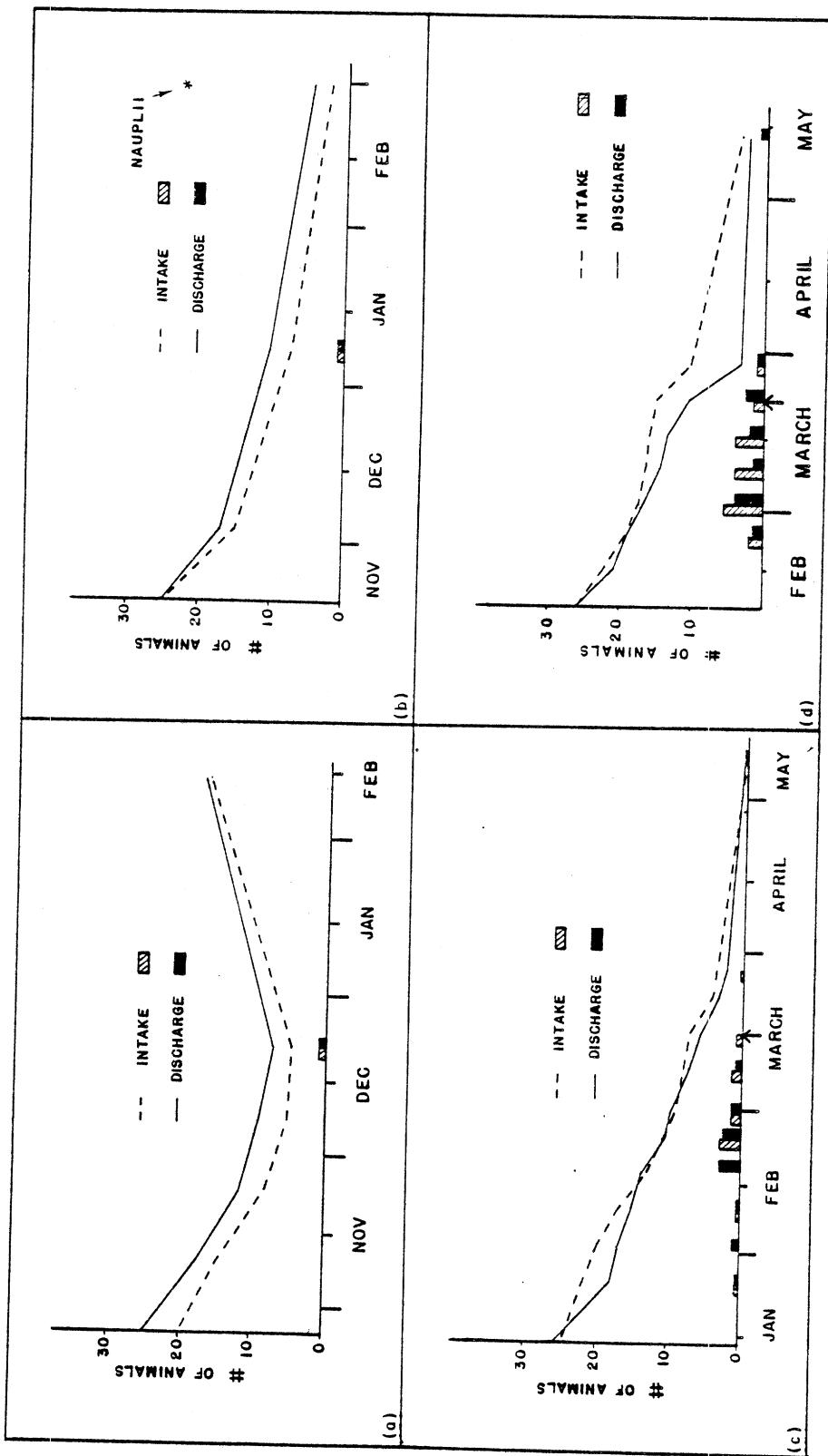


FIG. 46. The survival of Cyclops spp. copepodites in cultures of these organisms collected from the intake and discharge waters on a) 17 October 1975, b) 20 November 1975, c) 14 January 1976, and d) 11 February 1976. Histograms refer to the number of ovigerous females. After March 18 (1) early copepodites were included with nauplii counts.

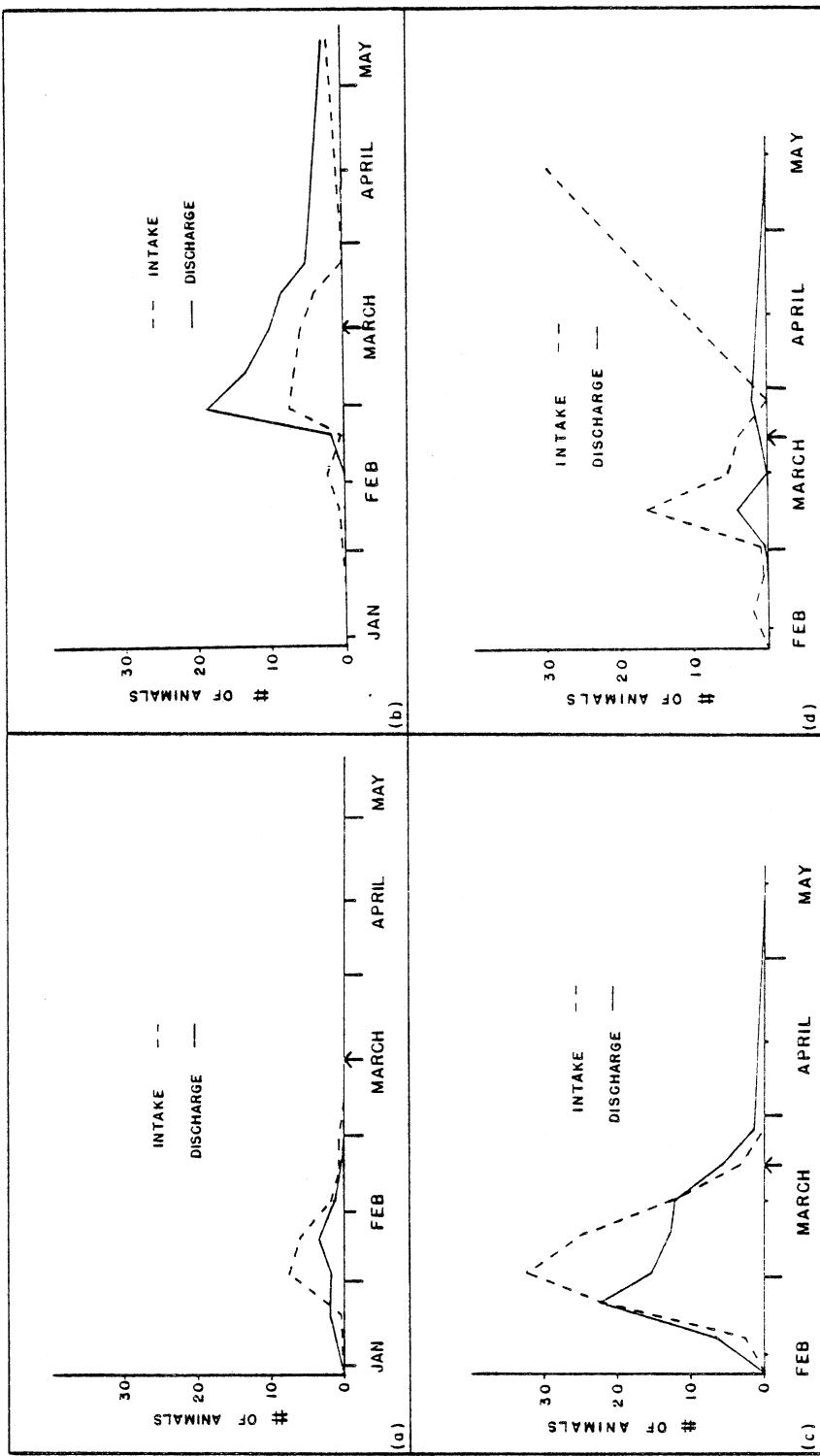


FIG. 47. The numbers of nauplii and immature copepodites (after March 18) produced in intake and discharge cultures of a) Diaptomus spp. and b) Cyclops copepodites collected on 14 January 1975, c) Diaptomus spp., d) Cyclops spp. copepodites collected on 11 February 1976.

sources of error other than those incorporated into the binomial model. Therefore, a non-parametric upper-sided median test was used. Only complete, non-tied pairs were used in the test. Calculations were performed on the AMDAHL 470V/6 computer at the University of Michigan.

Only immature and adult Diaptomus spp. and total zooplankton had significantly (at the 0.95 level) higher mortalities in the discharge waters than in the intake waters, (Table 14) although the differences were not significant at all incubation times. The differences between mean intake and mean discharge mortalities were generally small averaging less than 11%. Discharge mortalities for cyclopoid copepods and cladocerans were not significantly higher than intake mortalities.

Further investigations were undertaken to determine the relationship between zooplankton mortality, water temperature, pumping rate and animal size. Generally zooplankton mortalities in the discharge waters did not increase with discharge water temperature or ΔT . Mortalities tended to be negatively correlated with water temperature reflecting the high mortalities which were observed in the cold months of the year during storms and recirculation.

There was only a weak relationship between zooplankton size and immediate (0-hour) mortality over the 23 months of the study. Among the copepods, mean discharge mortalities varied from less than 1% to over 29% (Table 14). These mortalities had little relationship with zooplankton size (Fig. 48). While small (<.5mm) animals had mean discharge mortalities of approximately 15%, the mean mortalities of zooplankton approximately 1.5 mm in length, ranged from 1 to 29%. The largest zooplankton (3 mm) had a mean discharge mortality of only 12%. A similar lack of a strong relationship between copepod size and mortality was observed in the intake samples (Fig. 49). Most cladocerans ranged in size from 0.5 to 2.0 mm and their mean mortality in the discharge samples ranged from <1 to 47% with no strong correlation with length (Fig. 48). The largest cladoceran (12 mm), Leptodora kindtii, had a mean discharge water mortality of 28%. A similar lack of relationship between cladoceran length and mortality was observed in the intake samples (Fig. 49). Correlations (r) between size and mean taxon mortality in the intake and discharge samples were not significant for copepods or cladocerans.

Some taxa had very high mortalities in the intake samples and these mortalities were probably an artifact of our sampling techniques. It is doubtful that as many as 20% of the immature Tropocyclops prasinus mexicanus copepodites, 40% of the Diaphanosoma leuchtenbergianum and 50% of the adult Epischura lacustris were dead before sample collection. Rather, they were probably killed during sample collections. Visual examination of the intake samples supports this. Many of the dead nauplii had ruptured body walls, and copepodites had torn or missing urosomes and antennules. Holopedium gibberum generally lost its gelatinous sheath and Leptodora kindtii frequently exhibited signs of physical damage. Bosmina longirostris, Eubosmina coregoni, and Daphnia spp. became trapped at the water surface in incubation

TABLE 14. Zooplankton taxa for which discharge mortality was significantly higher than intake mortality using the upper-sided median test.

Incubation	Taxon	P (attained level of significance)		Mean mortality difference (Discharge % Dead - Intake % Dead)
0 hr.	<i>Diaptomus minutus</i> C6	0.002		9.7%
6 hr.	<i>Diaptomus</i> spp. C1-C5	0.048		6.5%
	<i>Diaptomus minutus</i> C6	0.014		5.5%
	<i>Diaptomus oregonensis</i> C6	0.003		4.8%
24 hr.	<i>Diaptomus oregonensis</i> C6	0.046		10.9%
Major Zooplankton Category Results				
0 hr.	<i>Diaptomus</i> spp. C1-C6	0.039		3.3%
6 hr.	Calanoid copepods C1-C6	0.003		4.1%
	Calanoid copepods C1-C5	0.008		6.5%
	<i>Diaptomus</i> spp. C1-C6	0.024		4.5%
	<i>Diaptomus</i> spp. C6	0.040		5.3%
	Total Zooplankton	0.036		1.9%
24 hr.	Calanoid copepods C1-C5	0.013		1.0%

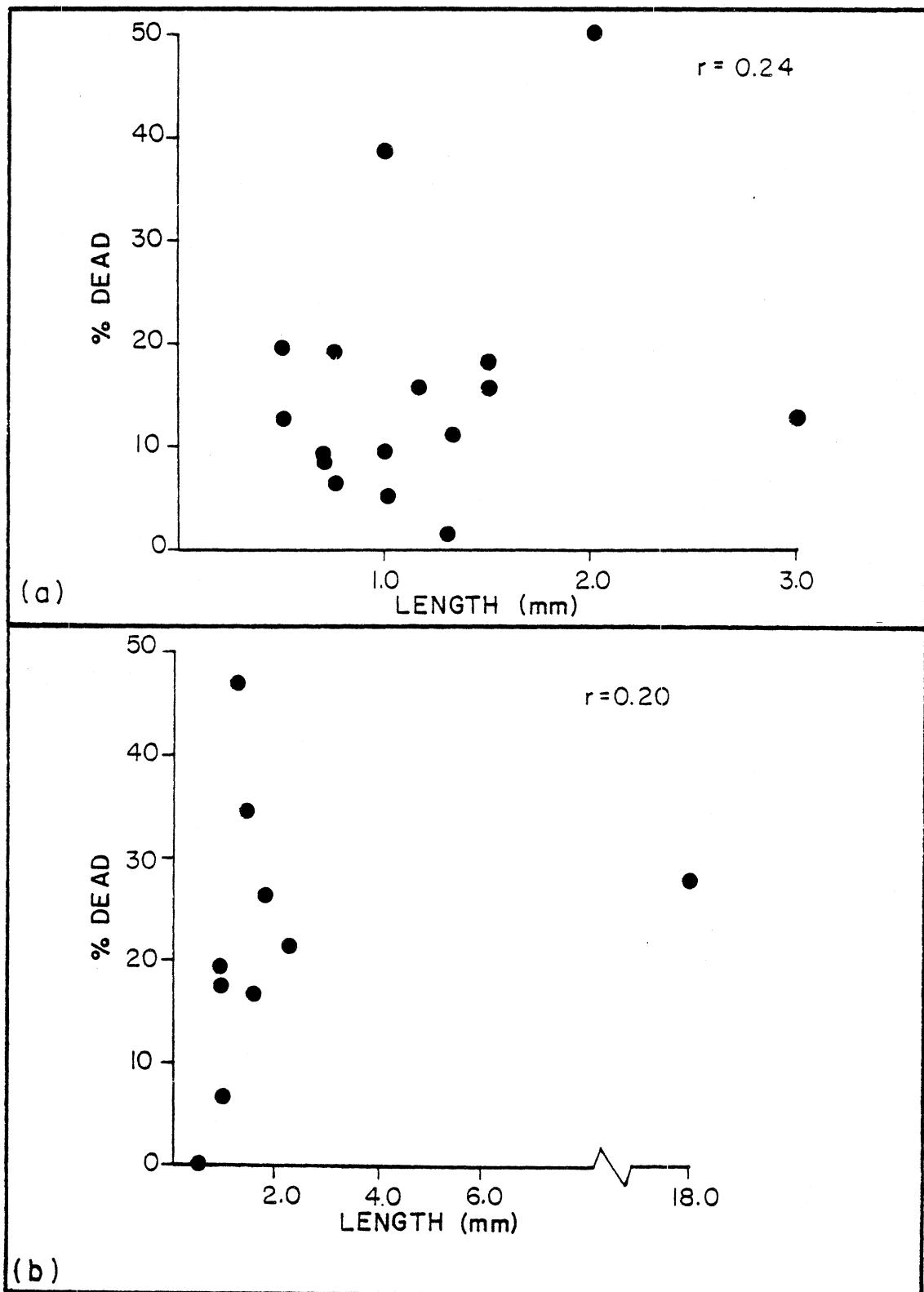


FIG. 48. Mean immediate (over 23 months) discharge mortality versus length for a) 16 copepod taxa, b) 10 cladoceran taxa.

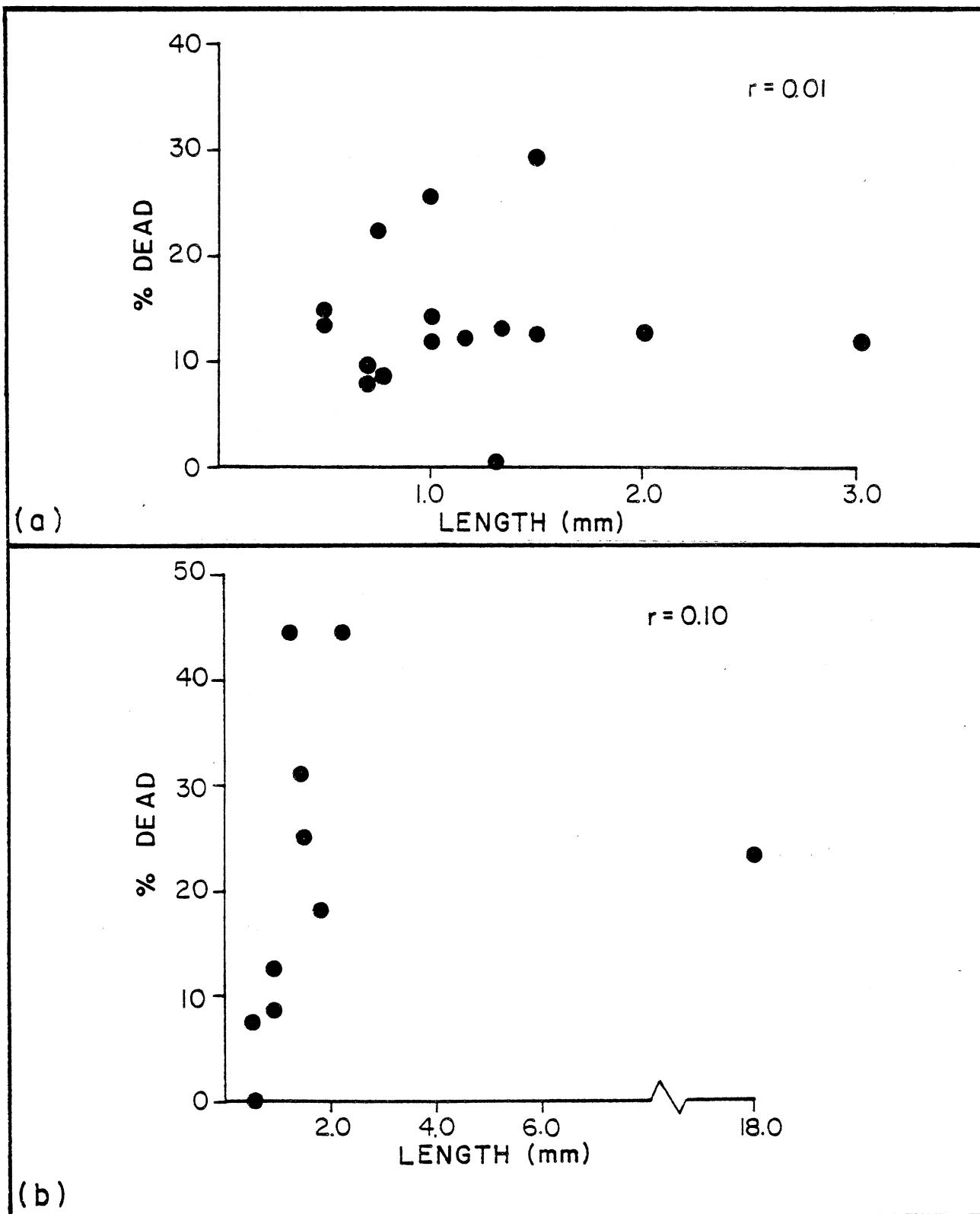


FIG. 49. Mean immediate (over 23 months) intake mortality versus length for
a) 16 copepod taxa, b) 10 cladoceran taxa.

and counting chambers when air bubbles collected under their carapaces. There is some evidence that this 'gas-bubble' disease is lethal (Nebeker 1976). Zooplankton collected in the discharge samples also exhibited similar signs of physical damage. These collection-induced mortalities undoubtedly had an effect on our ability to detect mortalities due to plant passage, particularly since these latter mortalities were relatively low. Random variations in collection mortality probably accounted for the fact that, on occasion, zooplankton mortalities were higher in the intake samples than in the discharge samples both on the taxonomic level and on the total zooplankton level.

DISCUSSION

The results of the mortality studies suggest that plant passage is lethal to only a small percent of the zooplankton which pass through its cooling system. The mean 0-hour mortality for total zooplankton was 11.8% in the intake waters and 12.0% in the discharge waters. These values were similar to mortality estimates obtained in other power plant studies on Lake Michigan (Industrial Bio-Test 1975; Limnetics 1976). Total zooplankton mortalities were slightly higher averaging 15.7% in the intake waters and 16.2% in the discharge waters after 24 hours of incubation.

Total zooplankton mortalities varied from month to month with intake mortalities ranging from 2% to 50% and discharge mortalities from 5% to 40%. Mortalities did not increase with discharge water temperature or with ΔT suggesting that under current operating conditions, water temperatures do not approach the upper lethal limit for most zooplankton. It is probably only when water temperatures exceed 35 to 40°C (Drost-Hansen 1969) or ΔT 's approach 20°C (Davies and Jensen 1974) that significant percentages of zooplankton are killed as a result of thermal stresses during plant passage.

Zooplankton mortalities often were highest during storms (January 1976) and recirculation (February, March 1975). High mortalities during recirculation may have resulted from repeated exposures to the mechanical and thermal stresses of condenser passage. The high zooplankton mortalities observed during the January 1976 storm may have been an artifact. During storms, detrital zooplankton and other debris are resuspended from the sediments and drawn into the plant. While we do not enumerate decaying zooplankton, freshly-killed and detrital zooplankton are not always physically distinct, particularly in colder waters (i.e. during winter) when dead zooplankton require a period of days to exhibit visible signs of decay (Wheeler 1967). Alternatively, violent wave activity generated during storms may have killed large numbers of zooplankton in the shallower areas of the lake.

At the genus or species level, there was no evidence of increasing mortality in the discharge waters with increasing water temperature or ΔT , and only a weak relationship between zooplankton size and mortality. The mean difference between zooplankton mortality in the discharge waters and in the

intake waters ranged from 0.8% to 24.6% (at 0-hours) for most of the numerically dominant zooplankton genera used in the statistical analyses of the preoperational and operational lake survey data (Section 2). However, some of these differences were negative. The estimated mean mortality for the rare taxa exhibited wide variations between samples and incubation times. In many instances, there was a large negative difference between the mean mortality in the discharge samples and the mean mortality in the intake samples. These incongruencies were related to the small sample sizes involved. Only a few organisms were counted, and a difference in one or two dead organisms had a major effect on the mortality estimate. Conversely, a difference in one or two dead organisms had a smaller effect on the mortality estimate for the numerically dominant taxa where many animals were counted in each sample.

The mortality data were variable not only from month to month but from sample to sample and subsample to subsample. Subsample variability was often large. In January 1975, estimated total zooplankton mortality ranged from 6% to 24% in a series of 14 subsamples from 7 samples collected from the same location on the same day (Evans 1975). Sample variability was also large as indicated by the May 1997 heterogeneity study. Estimated total zooplankton mortality ranged from 0.8% to 6.9% (Tables 11, 12) in a series of samples collected from the same location in the intake forebay over a period of three days. Since most of the mortality in both the intake and discharge samples was a result of injury incurred during sample collection, any sampling variability reduces our ability to detect mortality resulting from plant passage.

There are several ways to estimate the percent of zooplankton killed by plant passage. One way is to use the results of the statistical analyses. According to these tests, differences between total zooplankton mortalities in the discharge waters and in the intake waters were not statistically significant, suggesting that zooplankton were not killed during plant passage. However, Diaptomus spp. copepodite (C1 to C6) mortalities were significantly higher in the discharge waters (at 0-hours) than in the intake waters. The mean difference over the 23-month period was 3.3%. Since these zooplankton accounted for an average of 30.8% of the total zooplankton, this suggests that on the average at least 1.0% of the zooplankton passing through the plant were killed each month.

Another way to estimate the mean mortality of total zooplankton at 0-hours is to subtract the mean mortality of zooplankton in the intake waters (11.8%) from the mean mortality of zooplankton in the discharge waters (12.0%). The resulting value, 0.2% is an estimate of the percent of total zooplankton which were immediately killed by plant passage. However, this calculation does not correct for the percent of dead zooplankton which were in the intake samples. The calculation can be corrected by subtracting the mean intake mortality from 100, and then dividing the mean discharge mortality minus the mean intake mortality by this difference, and multiplying the quotient by 100. The resulting value, 0.23%, is larger than the uncorrected estimate and will increase as the percentage dead in the intake increases.

We have serious doubts that our sampling program is sensitive enough to detect a condenser-passed mortality of only 0.2% particularly when mean intake mortalities were 11.8%. This indicates that in the discharge waters, of 1,000 zooplankton which we examined, an average of 120 were dead, but only 2 were killed as a result of plant passage. Statistical analyses suggest that at the total zooplankton level no significant numbers of zooplankton were killed by plant passage but, at the genus and species levels, significant percentages of some zooplankton were killed by plant passage. These inconsistencies in the analytical results are related to the large sampling mortality and the relatively large variations in this mortality compared to mortality produced as a result of plant passage. Therefore, while the statistical analyses of the total zooplankton data at 0-hours (1975, 1976) suggests that zooplankton were not killed by plant passage, we believe that our sampling program was not sensitive enough to measure the real mortalities which occurred. We do not know the percent of zooplankton killed by plant passage. On the average, it was certainly less than 12%, the mean mortality of total zooplankton in the discharge samples, and was probably in the 1 to 2% range.

In the following section, we use the zooplankton mortality of the discharge sample to estimate the upper limit for the numbers and biomass of zooplankton killed by plant passage and discharged into the lake. In addition, we use the 12% mean discharge mortality value in estimating the deposition rate of these detrital zooplankton. Calculations are also performed using the 100% value. We believe that it is prudent to use this higher value (discharge mortality) since we do not estimate zooplankton mortalities at the discharge jets. Water velocities are high and shear forces great, and it is probable that zooplankton experience additional mechanical stresses at this location which result in higher mortalities due to plant passage than our data would suggest.

Even if 100% of the zooplankton were killed immediately following condenser passage, it is unlikely that these losses would be detected in the lake using conventional monitoring techniques. Over the discharge jets, condenser-passed water was rapidly mixed with lake water, so that the water column often contained less than 30% condenser-passed water (and zooplankton) (Section 1). A 12% loss of zooplankton due to condenser passage would have resulted in a net water column zooplankton loss of only 4.2%. If all the zooplankton were killed during plant passage, this would represent a loss of 30%. These losses cannot be detected over the discharge jets. In this highly turbulent area, dead zooplankton remained in suspension and were not physically lost from the water column. Since these organisms were freshly killed, they did not exhibit any physical signs of decomposition. Consequently these organisms were indistinguishable from living zooplankton which were collected in the same samples, preserved, and later examined in the laboratory.

Significant settling of zooplankton from the water column probably does

not occur within the ΔT 1.6 $^{\circ}$ C isotherm (Section 4). At this isotherm, condenser-passed water and zooplankton account for approximately 16% of the plume water. Assuming a zooplankton mortality of 12% and complete settling from the water column at this isotherm, only 1.8% of the zooplankton would have been lost. A kilometer away at the ΔT 0.5 $^{\circ}$ C isotherm, this loss would have been only 0.6% if 12% of the zooplankton were killed by plant passage and 5% if all zooplankton were immediately killed following condenser passage. Such losses cannot be detected with conventional sampling techniques. The coefficient of variation between successive net hauls at the same station is approximately 10% and the coefficient of variation between stations located in the same depth of water may reach 50%. If the true mortality estimate for total zooplankton due to condenser passage is as low as 1%, the net loss of zooplankton at the ΔT 0.5 $^{\circ}$ C isotherm would be approximately 0.05%. Therefore it is not surprising that significant losses in zooplankton numbers were not detected in the inshore plume zone where these small losses in zooplankton numbers were masked by large spatial and temporal variations in zooplankton numbers.

SECTION 4

NUMBERS AND BIOMASS OF ZOOPLANKTON PASSING THROUGH THE POWER PLANT AND SETTLING TO THE SEDIMENTS

INTRODUCTION

The entrainment program, in addition to estimating the percent of zooplankton killed during condenser passage, also monitors the concentration and composition of zooplankton passing through the plant. This information has several applications. By knowing the rate at which the plant withdraws water from the lake, estimates can be made of the number of zooplankton which pass through the plant and of the number killed before discharge into the lake. This information can also be expressed in terms of dry weight. Since a significant number of dead zooplankton may settle to the sediments and locally enrich an area, biomass calculations are of particular interest.

The information on zooplankton abundance in the inshore area between November and March has been obtained from the entrainment program since hazardous lake conditions prevented cruises from being conducted during these months. The entrainment program provides the opportunity to collect samples (from a standard location) throughout the year with minimal cost and maximum flexibility.

MATERIALS AND METHODS

Zooplankton were collected once a month from the intake forebay (MTR1-5, 5 m) and from the discharge forebay of Unit 1 at sunset, midnight, sunrise, and noon. Sampling at the four times compensated to some extent for patchiness and diel differences in zooplankton vertical distribution. Hale diaphragm pumps were used to simultaneously collect samples from the two locations. Water passed from the pump (Fig. 50), through a 30-cm diameter, 158 μ aperture net suspended in a barrel of water. A flowmeter located in the outflow pipe measured the volume of water filtered. Initially, sampling periods were two minutes but later were increased to five minutes in order to reduce the variance between replicate samples.

A total of 16 samples (2 locations x 4 times x 2 replicates) were collected each month. Additional samples were collected at noon at weekly or biweekly intervals in June, July, and August 1976 to provide more detailed information on zooplankton population dynamics. All samples were examined according to the same techniques described in Section 1 for the samples collected at the species stations. Station mean and additional summary data are reported in the Appendix (Tables 91-138).

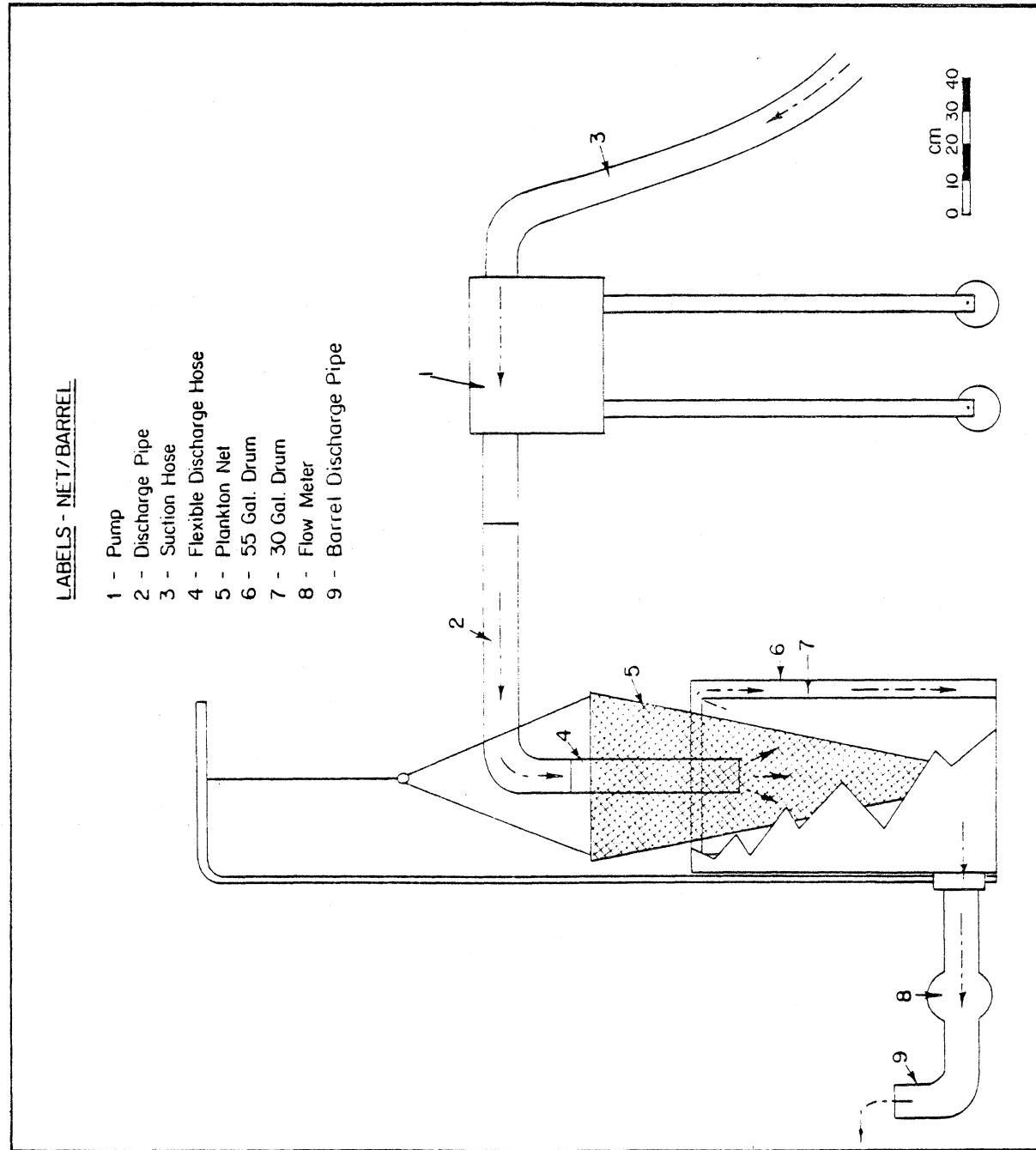


FIG. 50. Pump and net arrangement for zooplankton entrainment abundance samples.

RESULTS

Seasonal Concentration of the Major Zooplankton Taxa in the Cooling Waters and in the Inshore Region

The mean concentrations of the major zooplankton taxa in the cooling waters were calculated each month to determine seasonal patterns in numbers and composition. For comparative purposes, the mean concentration of zooplankton in the water column overlying the intake structures was estimated. The concentrations were estimated by averaging zooplankton abundances at all stations within the 10-m depth contour. Depending on the cruise, 7 to 13 stations (14 to 26 samples) were used to estimate the mean. Zooplankton populations several kilometers from the intake structures did not differ consistently from populations near the plant site (Section 1). Since lake currents transport water several kilometers per day (Ayers et al. 1967), stations beyond the immediate intake area were included to provide a better estimate of zooplankton population during the 16 to 19 hours of the entrainment study. Cruises were generally conducted one day after the entrainment study.

For the most part, zooplankton occurred in similar concentrations in the entrained water and in the inshore region of the lake. There were no consistent differences (Fig. 51) in the abundance estimates for total zooplankton, immature and adult Diaptomus spp., Eurytemora affinis copepodites, immature Cyclops spp. copepodites, Bosmina longirostris, and Eubosmina coregoni. However, adult Cyclops spp. (primarily C. bicuspidatus thomasi) and to a lesser extent Daphnia spp. occurred in greater concentrations in the entrainment samples, and nauplii and Asplanchna spp. occurred in lower concentrations than in the lake samples.

Large variations in zooplankton abundance were observed during the summer of 1976 when additional entrainment samples were collected. In some instances, taxa concentrations increased or decreased tenfold from one week to the next (Fig. 52). Differences in abundances were probably due to temporal variations in zooplankton birth and death rates and to differences between water masses. These large weekly variations reveal the limitations of data collected only once a month and used to provide 'representative' estimates of zooplankton populations during that month. Since zooplankton concentrations in the cooling waters were similar to those in the inshore region (for the most part) more frequent entrainment sampling provides valuable information on zooplankton population dynamics not only during the four or five months of the year when cruises are not conducted but also during the summer when zooplankton generation times are short and population shifts can occur very rapidly.

Epibenthic and Benthic Copepods and Cladocerans

Epibenthic and benthic copepods and cladocerans were rarely collected in

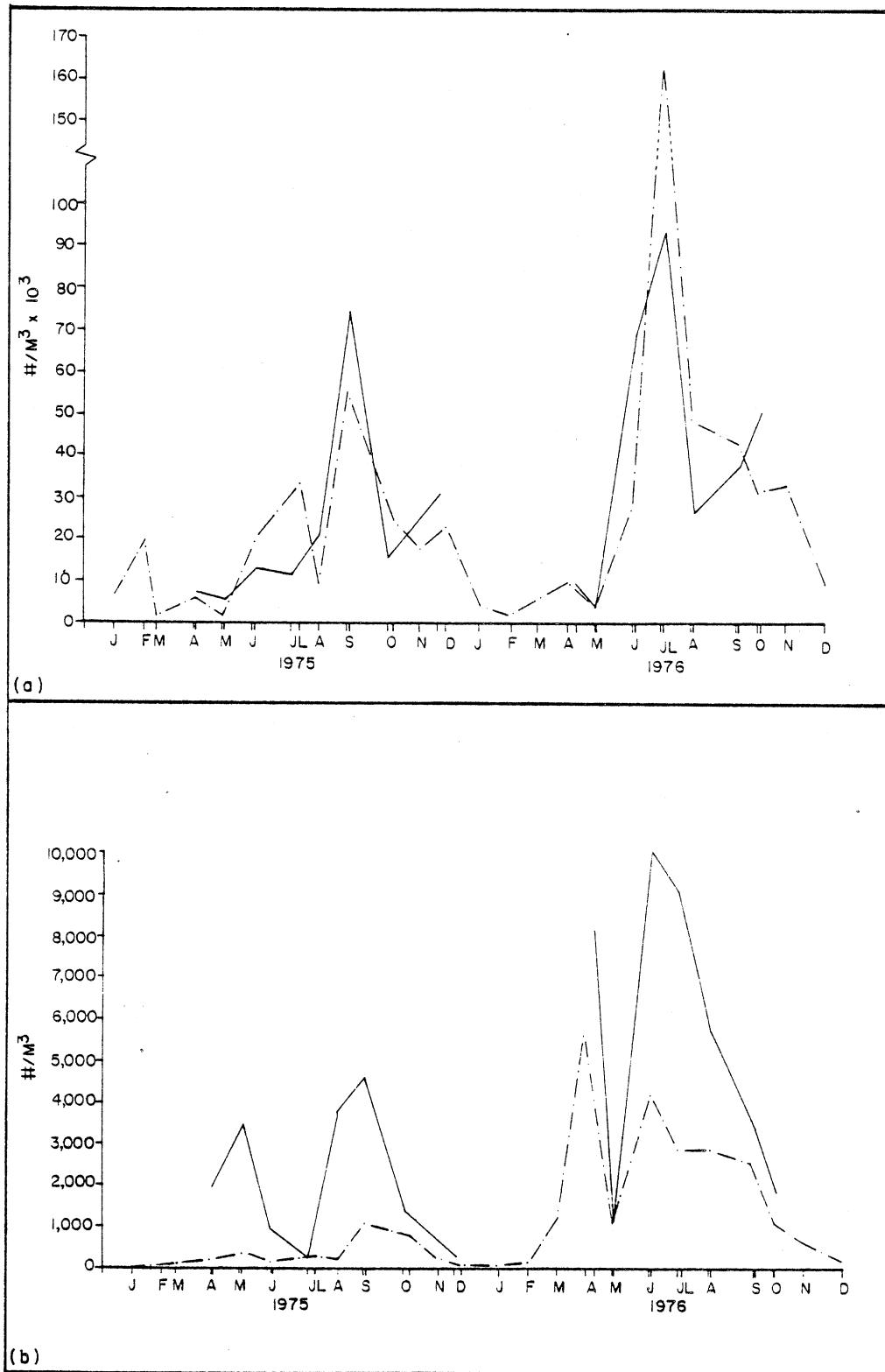


FIG. 51. Graphical comparisons of zooplankton densities in the entrainment abundance samples (----) and in the inshore zone (—). Entrainment data points represent the mean of up to four sampling times (sunset, midnight, sunrise, and noon) and inshore zone data points represent the mean of up to 13 stations. a) Total zooplankton, b) copepod nauplii.

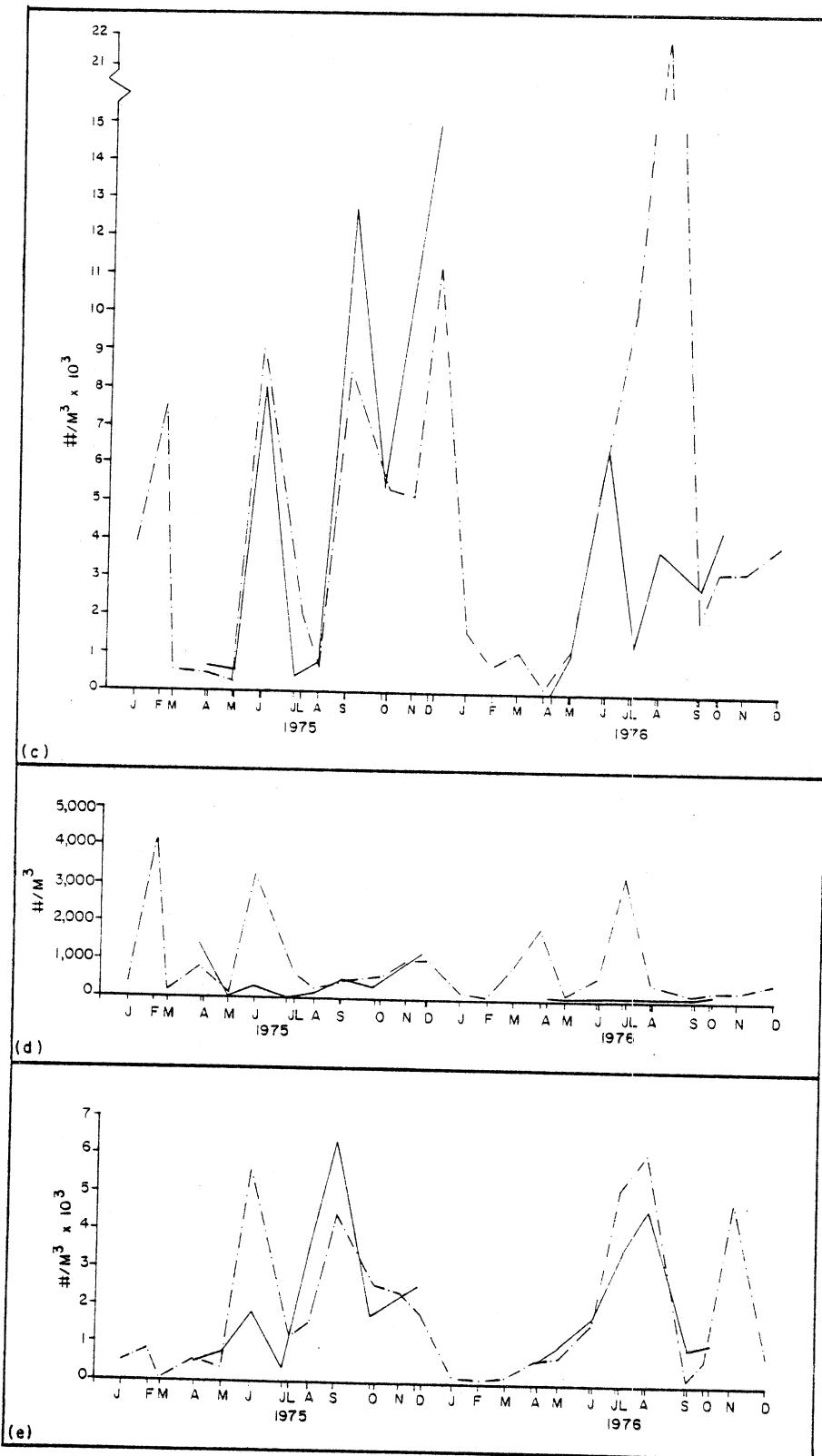


FIG. 51 continued. c) immature cyclopoids, d) adult Cyclops spp., e) immature Diaptomus spp.

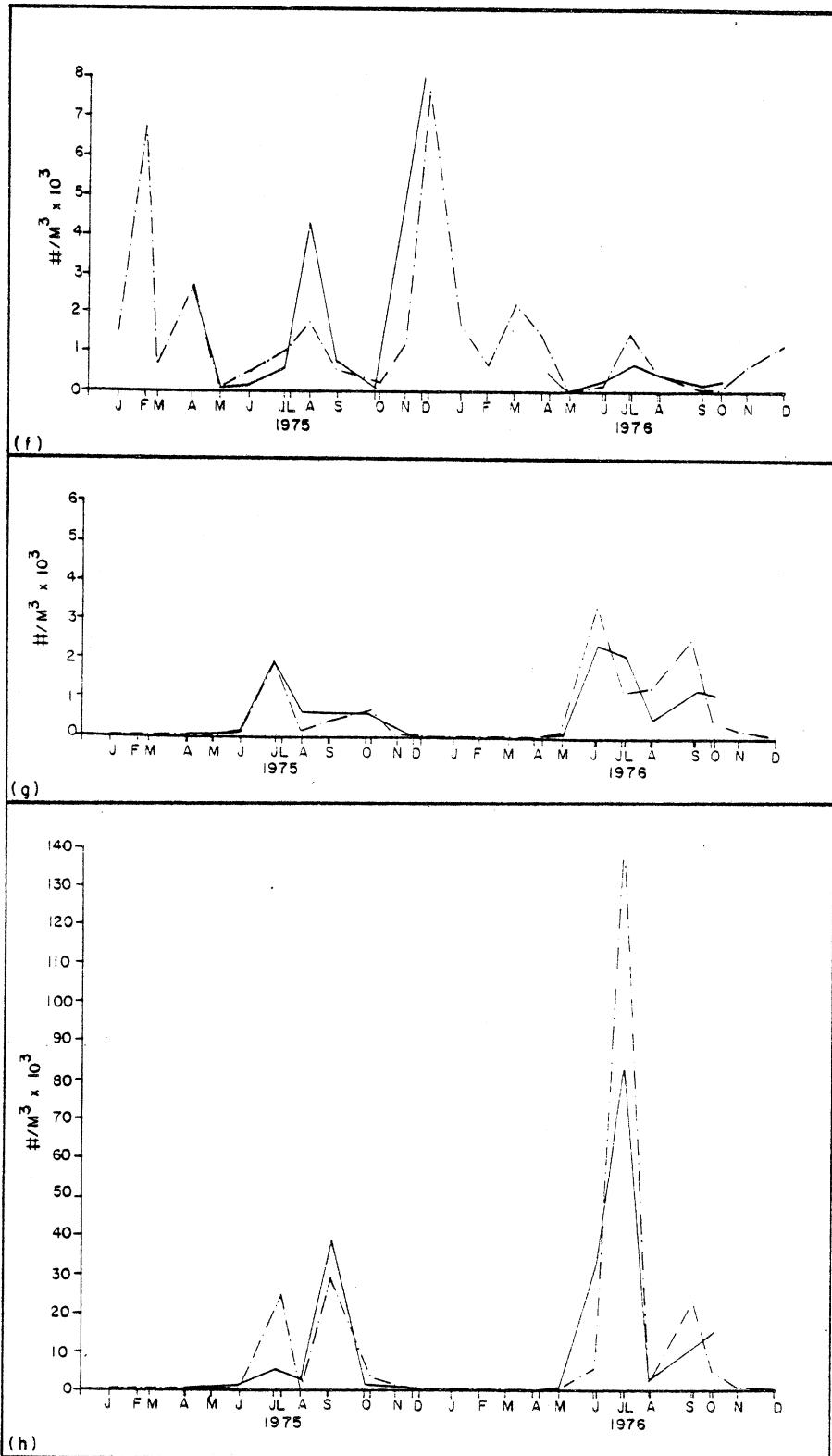


FIG. 51 continued. f) adult Diaptomus spp., g) Eurytemora affinis, h) Bosmina longirostris.

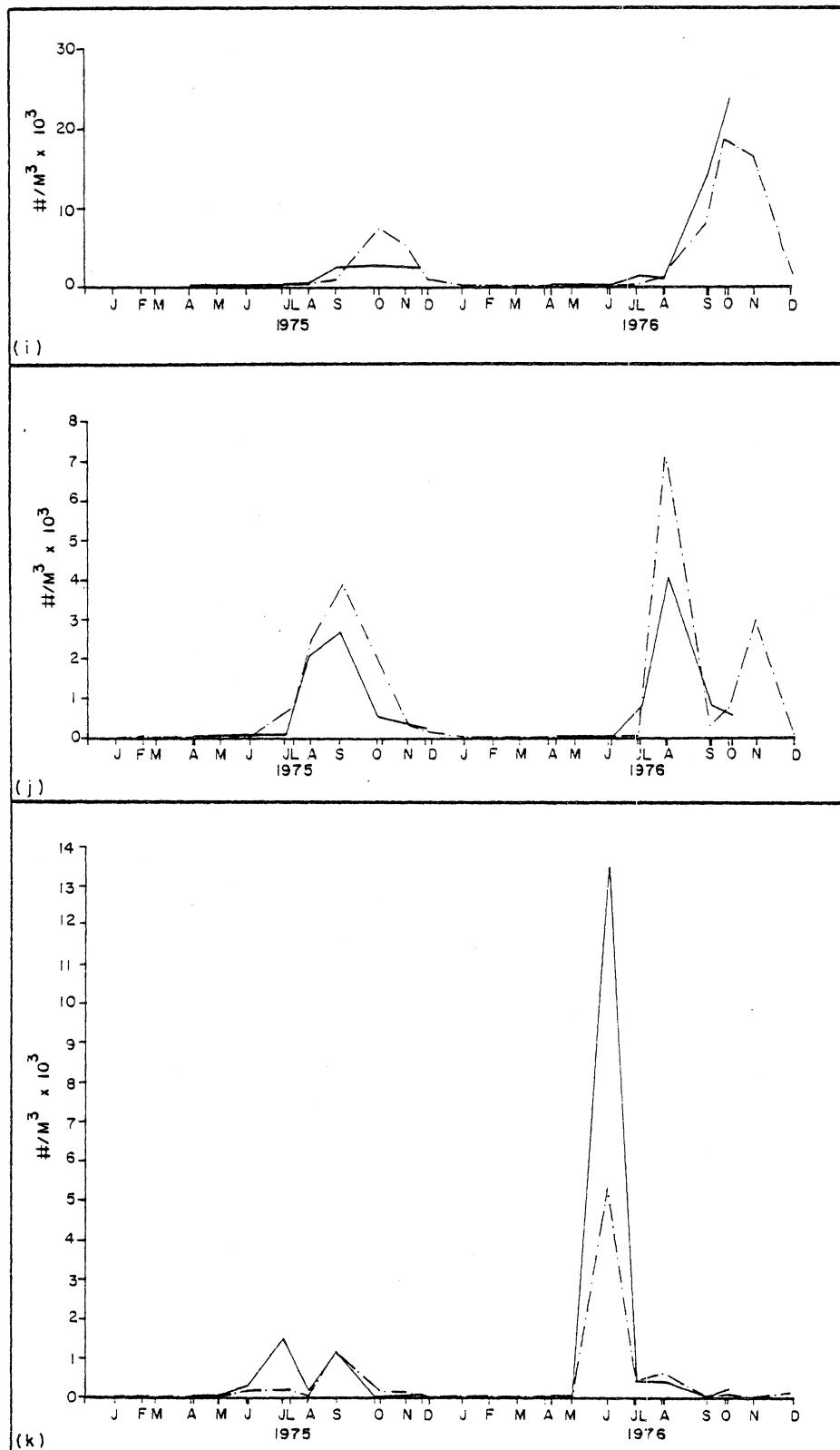


FIG. 51 continued. i) *Eubosmina coregoni*, j) *Daphnia* spp., and k) *Asplanchna* spp.

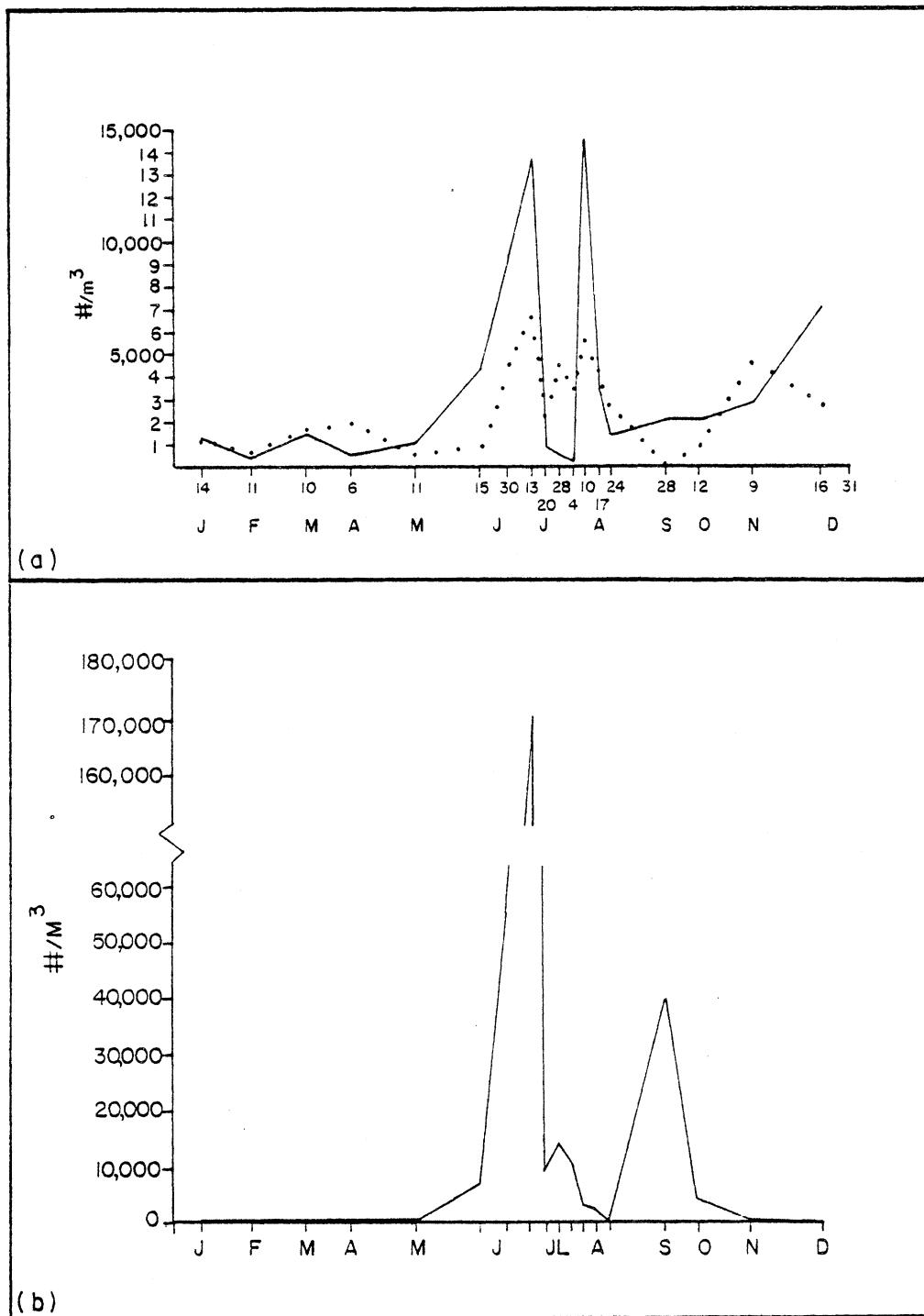


FIG. 52. Variation in abundance of selected zooplankton taxa collected in entrainment abundance samples in 1976. Samples were collected weekly between July 23 and August 24. All samples were collected at noon. a) Cyclops spp. (solid line) and Diaptomus spp. (dotted line), b) Bosmina longirostris.

the lake surveys (Section 1, Table 3) and, while still not abundant, they occurred in higher concentrations in the entrainment samples (Fig. 53). Both sampling series underestimate the concentrations of these animals, since they inhabit the sediment-water interface. This area is not adequately sampled in the lake survey program since plankton nets do not sample the lower meter of the water column. The openings of the intake pipes are one meter above bottom and it is unlikely that significant fractions of epibenthic and benthic populations are drawn into the power plant except during storms.

Concentrations of epibenthic and benthic copepods and cladocerans may have been on the increase since the construction of plant intake and discharge structures began. Most taxa occurred in higher concentrations in 1976 than in 1975 (Fig. 53). While these differences may merely reflect lake-wide variability, they may also be related to plant operation. Preliminary examination of the 1977 entrainment data suggests that these taxa are continuing to increase in concentration. Increases may be limited to the riprap area where a variety of animals including hydra, crayfish, sculpins, and carp have increased in numbers since plant operation (S.C. Mozley, J. Dorr pers. comm.).

Numbers and Biomass of Zooplankton Passing Through the Power Plant and the Estimated Maximum Losses

Each month, billions of zooplankton passed through the power plant (Fig. 54) with the lowest numbers occurring in the winter when zooplankton populations were smallest. More zooplankton passed through the power plant in 1976 than in 1975, primarily because of the greater zooplankton populations in 1976; plant pumping rates were approximately equal in the two years. The upper limits for numerical losses were estimated by assuming that immediate (0-hour) discharge mortality represented the maximum loss of zooplankton within the vicinity of the discharge jets. The actual loss was probably lower (Section 3). Greatest numerical losses occurred in the summer and autumn months when zooplankton populations were largest.

The seasonal trend for biomass of zooplankton passing through the power plant (Fig. 55) did not parallel the trend in numbers (Fig. 54). Seasonal biomass cycles were not distinct, and biomass was frequently high during the colder months when large adult Diaptomus spp. and the later copepodite stages of Cyclops bicuspidatus thomasi dominated the zooplankton. The estimated biomass of zooplankton passing through the power plant ranged from 229 to 8485 kg dry wt./month and averaged 3200 kg. dry wt./month (72,000 lb fresh weight/month). The upper limit for biomass losses was estimated to have ranged from 11 to 1345 kg. dry wt./month and averaged 412 kg dry wt./month (9,000 lb fresh weight/month). Over the 23 month period, a maximum of 12.2% of the biomass of living zooplankton passing through the plant was killed before being discharged to the lake. This compares quite closely to the upper limit for mean numerical mortality of 12.0% suggesting that plant passage is equally damaging to all sizes of zooplankton. This was also shown

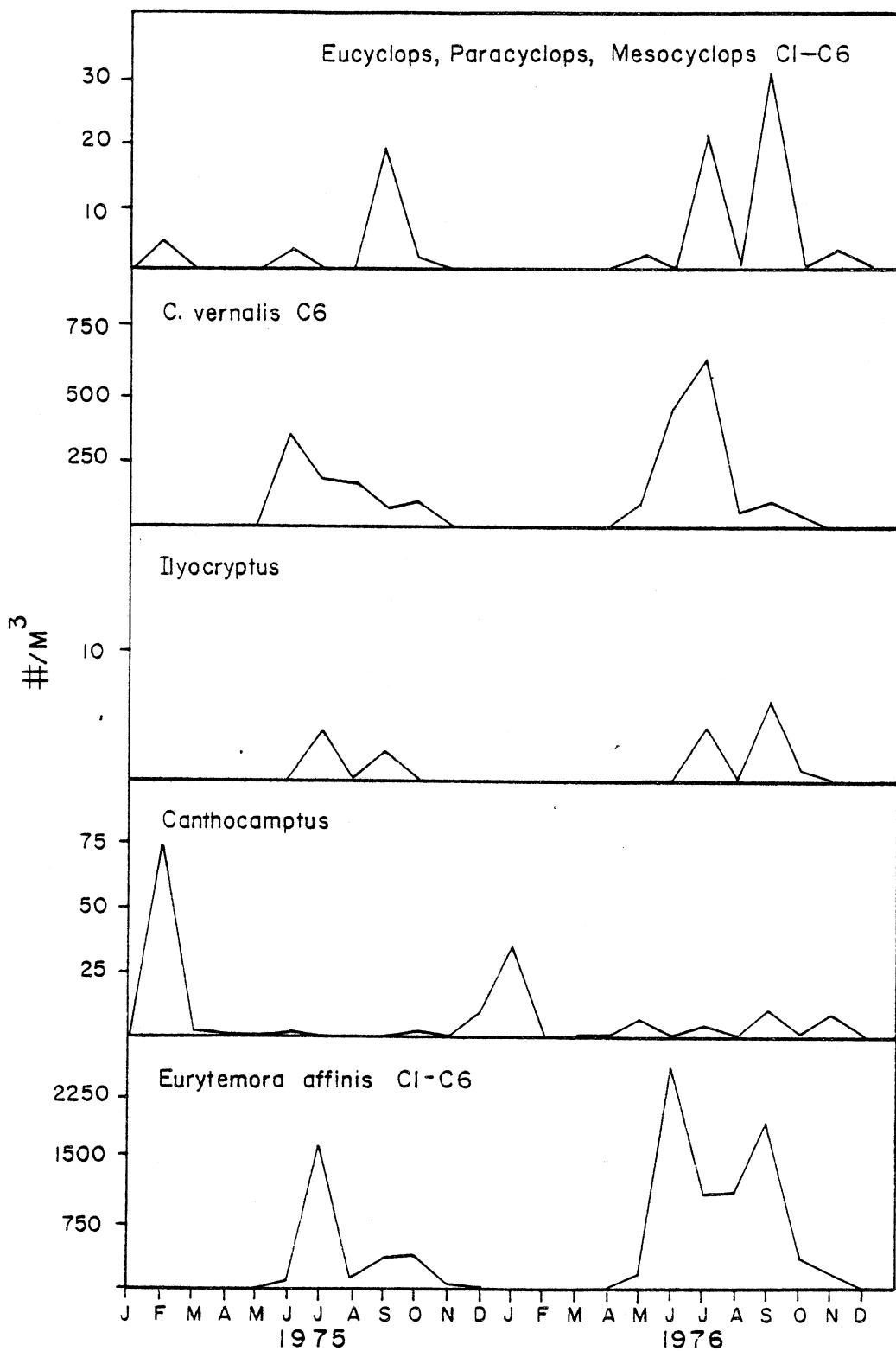


FIG. 53. Seasonal abundance of epibenthic zooplankton collected in the entrainment abundance sampling program.

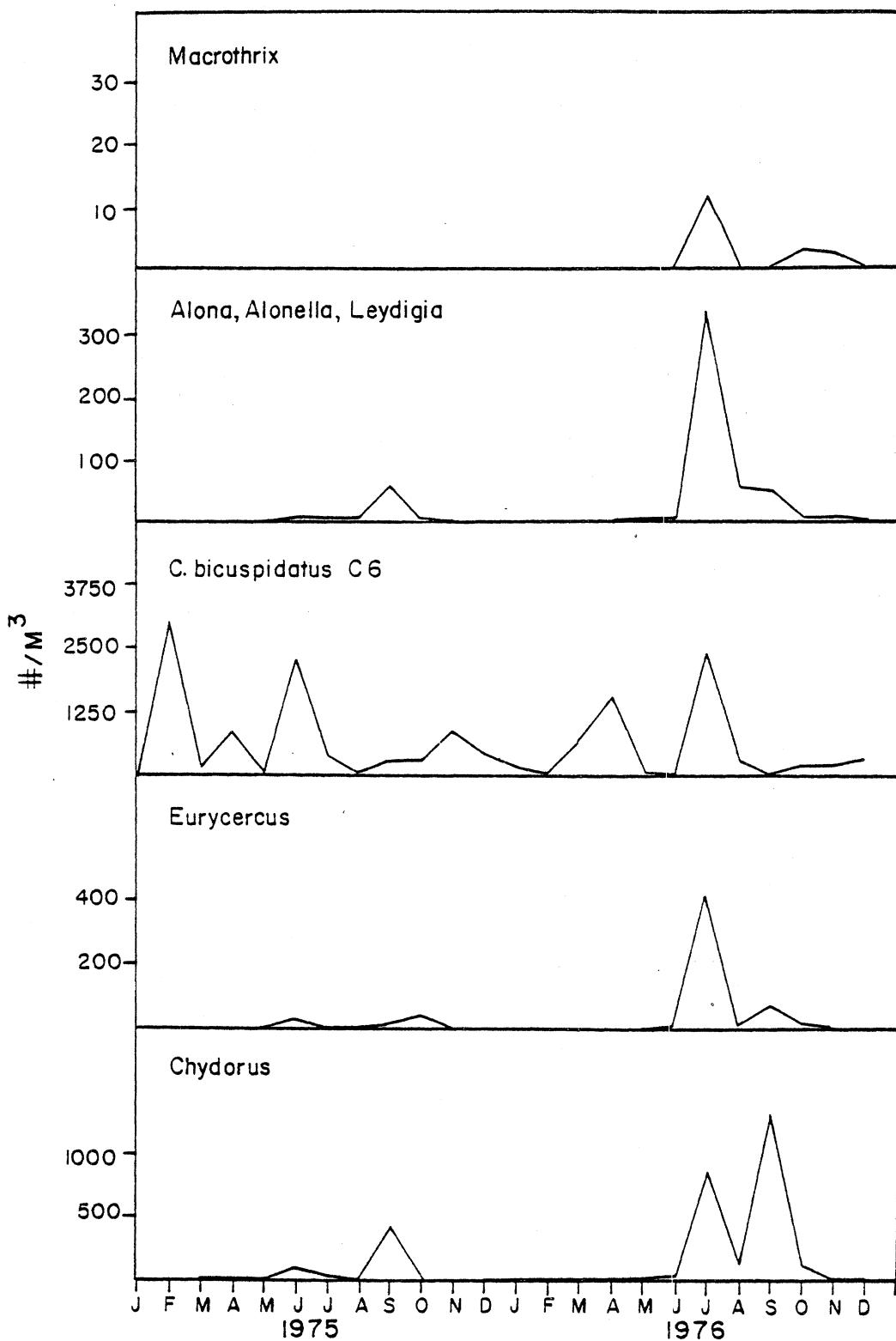


FIG. 53 continued. Alonella is synonymous with Disparalona.

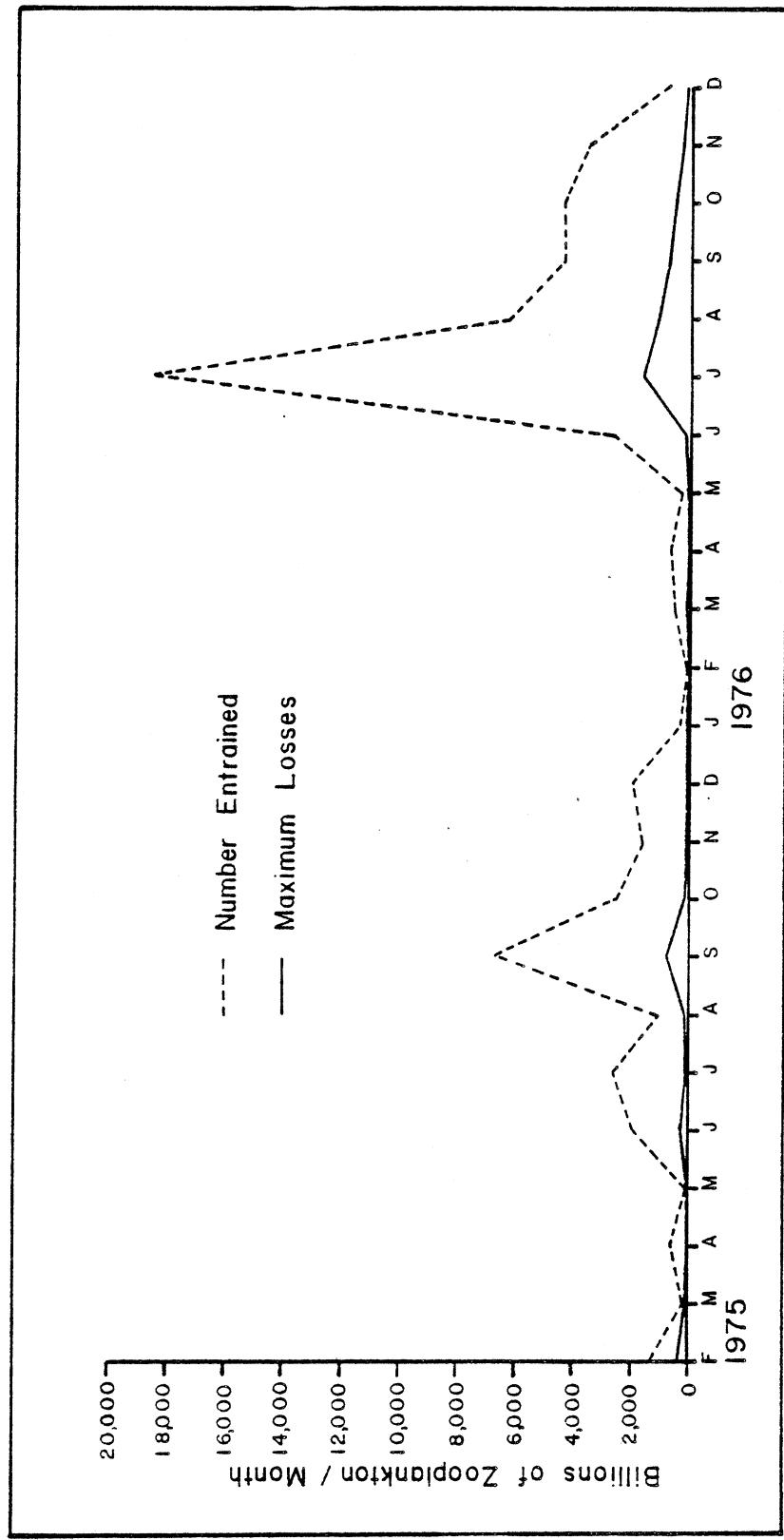


FIG. 54. Estimates of the number of zooplankton entrained and maximum numbers lost during 1975-1976.

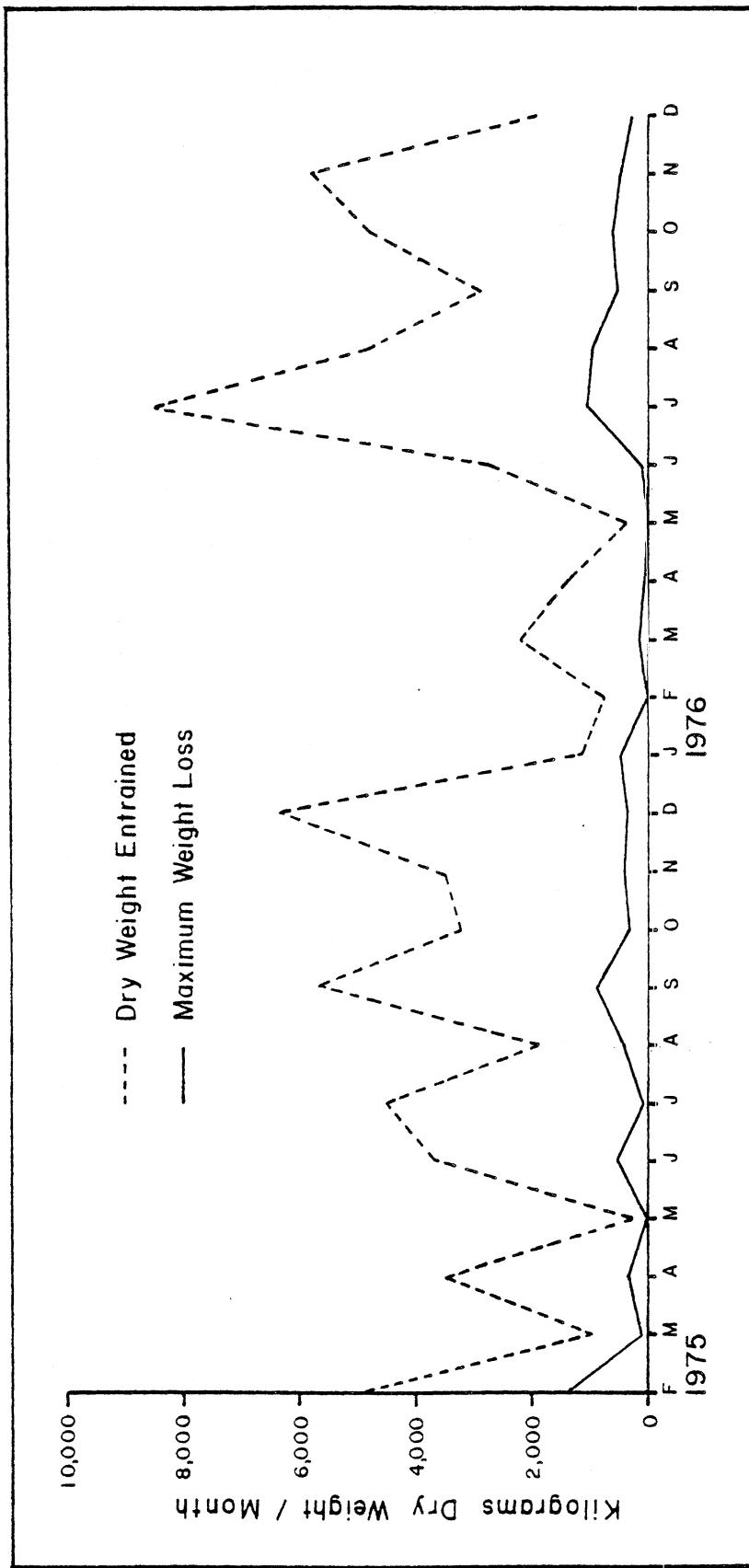


FIG. 55. Estimates of dry weight of entrained zooplankton and maximum losses during 1975-1976.

in Section 3.

Depositional Area of Zooplankton Killed During Condenser Passage

In 1974, calculations were performed to estimate the area over which zooplankton killed during condenser passage would settle from the water column to the sediments (Indiana and Michigan Power Company 1975). These calculations were simplistic and were presented as crude estimates of the minimum areal distribution and maximum deposition rate of killed zooplankton and were based on theoretical plume models and various assumptions. Since Unit 1 went into operation in 1975, the Cook power plant personnel have conducted an intensive program mapping the thermal plume on several occasions during each of four seasons of the year and have calculated the mean location of the thermal plume at the ΔT 3F° isotherm (Indiana and Michigan Power Company 1976, Fig. 56). Using these new data, some of the theoretical plume data, and 1975 and 1976 entrainment data, we recalculated a two-year mean deposition area and rate for zooplankton killed during plant passage.

Dead zooplankton were assumed to remain in suspension in the thermal plume until current velocities were reduced below 0.2 fps (6.1 cm/sec). Sediment particles 1 mm in diameter do not settle out of the water column until horizontal current velocities are reduced below 0.2 fps (Hjulstrom 1937). Because of their lower specific gravity, zooplankton probably remain in suspension until lower current velocities are attained. Theoretical plume models predict that current velocities along the plume center line decrease to 0.2 fps approximately at the ΔT 3F° isotherm (Indiana and Michigan Power Company 1975). We assumed that some zooplankton remain in suspension until this point and then begin sinking from the plume. The area over which the ΔT 3F° isotherm plume (Fig. 56) was expected to be located from 4-100% of the time (Indiana and Michigan Power Company 1976) was used to estimate the area over which zooplankton killed by condenser passage remained in suspension before beginning to settle from the water column.

The calculations assumed a measured zooplankton settling rate of 0.15 cm/sec (Table 15), a plume velocity of 0.2 fps (6.1 cm/sec) in a 3 m thick plume, and an ambient lake current velocity of 0.18 fps (5.5 cm/sec) to the north. This latter velocity was the mean lake current velocity measured by Ayers et al (1967) in the inshore region between May and October. The depth of the water at various locations along the plume was determined from known lake survey station depths and distances from shore. Then, at these locations, we assumed that zooplankton began settling at a rate of 0.15 cm/sec while drifting in a horizontal plane at 6.1 cm/sec through the 3 m thick plume, and then continued drifting at a velocity of 5.5 cm/sec below the plume until they sank to the lake bottom. By knowing the depth of the water column and zooplankton sinking rates, it was possible to calculate the time required for the zooplankton to reach the sediments. Knowing the horizontal current velocities allowed estimates to be made of the distance travelled along the horizontal plane. Trajectories were calculated along

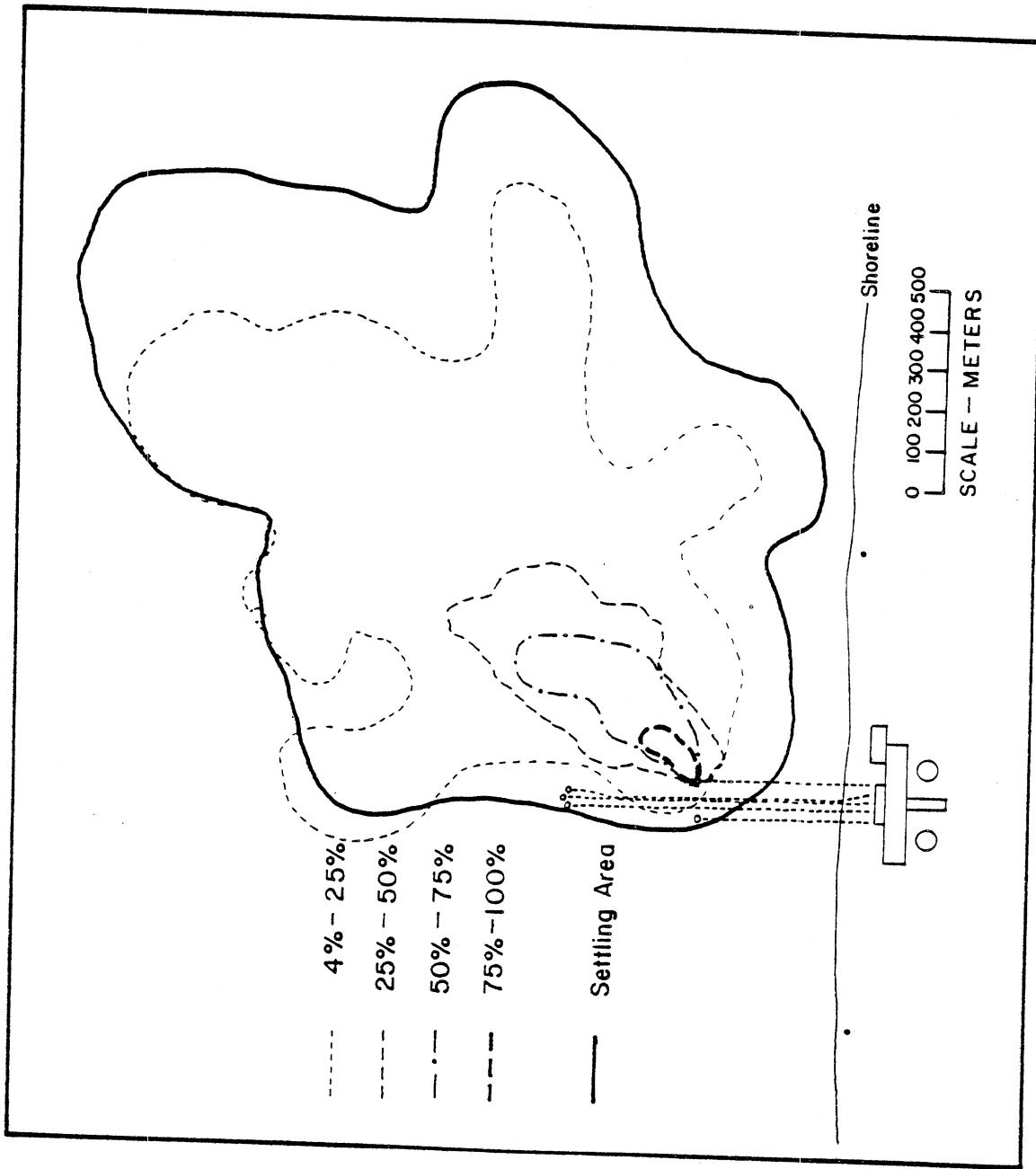


FIG. 56. The area over which 96% of the zooplankton killed during condenser passage settle to the sediments (solid line). The locations, by percentage of the monitoring time, of the $\Delta T = 3^{\circ}\text{F}$ thermal plume at 1 meter are also shown (dashed line). (After Indiana and Michigan Power Co., 1976.)

TABLE 15. Sinking rates of selected zooplankton taxa as measured in the laboratory.

Taxon	Formalin Killed		Heat Killed	
	n	cm.sec ⁻¹	n	cm.sec ⁻¹
nauplii	3	.09	2	.08
<u>Cyclops</u> C1			1	.09
<u>Cyclops</u> C2			8	.10
<u>Cyclops</u> C3			6	.13
<u>Cyclops</u> C4			8	.16
<u>Cyclops</u> C5			4	.16
<u>Cyclops bicuspidatus</u> C6 ♂			7	.17
<u>Cyclops bicuspidatus</u> C6 ♀	8	.18	4	.26
<u>Cyclops bicuspidatus</u> ♀ w/eggs			2	.32
<u>Cyclops vernalis</u> ♂			1	.17
<u>Tropocyclops</u> ♀			4	.12
<u>Tropocyclops</u> ♂			2	.20
<u>Diaptomus</u> C1	2	.07		
<u>Diaptomus</u> C2	1	.09		
<u>Diaptomus</u> C3	2	.10	1	.23
<u>Diaptomus</u> C4			2	.17
<u>Diaptomus</u> C5	1	.15	2	.15
<u>Diaptomus ashlandi</u> C6	1	.15		
<u>Diaptomus minutus</u> C6			4	.22
<u>Diaptomus oregoni</u> C6	1	.20	1	.22
<u>Epischura lacustris</u>	1	.44		
<u>Bosmina longirostris</u>	6	.16	7	.15
<u>Ceridaphnia quadrangularis</u>	1	.27	6	.23
<u>Chydorus sphaericus</u>			6	.26
<u>Daphnia retrocurva</u>	4	.22		
<u>Eubosmina coregoni</u>			5	.22
<u>Leptodora kindtii</u>	1	.31	1	.29
<u>Polypheus pediculus</u>	2	.38		

n=number of replicate determinations

various locations of the ΔT $3F^{\circ}$ isotherm, enclosing lines drawn (Fig. 56), and the area calculated.

The area over which 96% of the original deposition occurred was estimated to be 2.2 km^2 . The actual dimensions of the depositional area were closely approximated by the ΔT $3F^{\circ}$ plume. This new estimate of the depositional area compares favorably with previous estimates of 1.2 to 3.0 km^2 (at a lake current of 0.2 fps) primarily because the theoretical and measured plume maps were similar in area.

Depositional Rate of Dead Zooplankton

The depositional rate of zooplankton killed by condenser passage was calculated by dividing the estimated area of deposition (2.2 km^2) into the 23-month mean upper limit of biomass loss ($412 \text{ kg dry wt/month}$ or 13.5 kg/day). Over the two years of the study, the average deposition rate was estimated to be $6.1 \text{ mg/m}^2/\text{day}$. This rate was considerably lower than previous estimates of 319 to $579 \text{ mg/m}^2/\text{day}$ at a lake current of 0.2 fps (Indiana and Michigan Power Company 1975). Differences in the values were due to several factors. Biomass entrained varied from 47 to $143 \text{ kg dry wt./day}$ and was approximately one-seventh of previous estimates. Some of these differences were due to the fact that the original calculations were based on two-unit operation while only one of the two units of the power plant was in operation in 1975 and 1976. Secondly, we overestimated zooplankton biomasses in the inshore area in the 1975 calculations. Mean biomass was estimated to be 90 mg/m^3 over a 12-month period while the actual mean determined in 1975 and 1976 was 30 mg/m^3 . The improved biomass techniques utilized in 1975 and 1976 probably provided more accurate assessments of zooplankton dry weight in the inshore region than when the old filtration method was used (Section 1). Finally, we assumed a mean zooplankton mortality of 100% in the earlier calculations whereas a mean maximum mortality of 12.0% was used in the new calculations. Therefore lower pumping rates (factor of two), lower biomasses (factor of three), and lower zooplankton mortalities (factor of eight) were the major reasons for the differences in the results of the two calculations.

DISCUSSION

Although the zooplankton biomass loss due to condenser passage was estimated as ranging from 11 to $1345 \text{ kg dry wt./month}$ (maximum estimate), it is unlikely that the presence of these dead zooplankton had an adverse impact on the water or sediment quality of southeastern Lake Michigan. Most of the settling was predicted to have occurred over a relatively small area (2.2 km^2) of the lake with an average settling rate of $6.2 \text{ mg dry wt./m}^2/\text{day}$ (assuming a upper limit to mean zooplankton mortality due to plant passage of 12%).

In the previous study, we estimated that natural deposition rates in the

inshore region of southeastern Lake Michigan was $2.8 \text{ gm/m}^2/\text{day}$ (Indiana and Michigan Power Company 1975) which compared closely to the measured deposition rate of 0.21 to $1.91 \text{ gm/m}^2/\text{day}$ for Lake Ontario and the Bay of Quinte (Johnson and Brinkhurst 1971). Parker et al. (1977) in southeastern Lake Michigan measured sedimentation rates of $3.76 \text{ gm/m}^2/\text{day}$ ($0.376 \text{ mg/cm}^2/\text{day}$) in the upper 37 m of the water column at a station 13.2 km offshore. Sedimentation rates in the inshore and middle regions (less than 20 m of water) may be lower because the water is shallower but the greater productivity in the nearshore area may compensate for this. Nevertheless, assuming a natural sedimentation rate in the order of 2 to $4 \text{ gm/m}^2/\text{day}$, it is unlikely that an additional loading of dead zooplankton at a rate of $6 \text{ mg/m}^2/\text{day}$ would have had a significant impact on the sediments. If zooplankton mortality immediately following condenser passage were 100% , the loading rate would be only $50.8 \text{ mg/m}^2/\text{day}$. This loading is only $1.3\%-2.6\%$ of estimated natural sedimentation rates. Our mortality studies suggest that actual mortalities due to plant passage may be as low as 1% (Section 3) which would result in an additional loading rate of $1.0 \text{ mg/m}^2/\text{day}$ or 0.3 to 0.5% of natural deposition rates.

It is unlikely that much of the material which is killed during plant passage and settles out to the sediments has a long residence time in the immediate discharge area. Within the 10-m depth contour, currents and wave activity produce an unstable substrata. Observations conducted by SCUBA divers indicate that little detrital material accumulates at these depths during the summer and autumn (Ayers et al. 1973). More material accumulates at depths greater than 10 m but wave and current activity probably resuspend and redistribute much of this material.

SECTION 5

DETAILED COMPARISONS OF ZOOPLANKTON POPULATIONS WITHIN AND ADJACENT TO THE THERMAL PLUME

INTRODUCTION

In Sections 1 and 2, we showed that the lake monitoring program has not detected spatial alterations in zooplankton populations associated with plant operation. Such alterations have not been detected due to several factors including rapid dilution of condenser-passed water, low mortality of zooplankton during condenser passage, and the comparatively long time required for dead zooplankton to settle from the water column or to exhibit visible signs of decay. The low number of stations (<4) that contained plume water, and the fact that the plankton hauls sampled the entire water column and not only the overlying plume further reduced the likelihood of detecting such plant-related alterations in zooplankton populations.

The monitoring program provides little detailed information on zooplankton population structure in the vicinity of the plume. Small scale alterations in zooplankton populations may occur which, because of sampling procedures, are beyond the level of detection. In order to investigate this, we conducted an intensive study of zooplankton distributions within and adjacent to the thermal plume in September 1976. These data indicate the magnitude and areal extent of changes which can occur in zooplankton populations within the thermal plume.

MATERIALS AND METHODS

Eighty-four zooplankton samples were collected between 13:46 and 16:46 E.S.T. on September 25, 1976 from a depth of 1 m, along a series of 12 transects extending approximately 1800 m north and south of the discharge jets and 1600 m offshore (Fig. 57). A centrifugal pump and hose system was used to collect the zooplankton. Water passed from the 5.0 cm (2") diameter hose, through the pump, and then was discharged through a 7.6 cm (3") diameter hose and PVC pipe into a 50-gallon (0.2 m³) barrel of water. A 30-cm diameter, 158 μ aperture net was suspended in the barrel of water (to reduce structural damage to the zooplankton during filtration) and collected the plankton. The intake hose was equipped with a checkvalve (to aid in pump priming), a series of fairings, and a vane (to reduce turbulence during towing). A 23 kg (50 lb) cable depressor helped to maintain a low wire angle during sample collection.

Samples were collected for two minutes while the pump was in continuous operation and as the ship travelled along the transects. Ship speed was approximately 3.5 knots so that each two-minute sample was collected over an approximate distance of 200 m. Nearly 0.8 m³ of water was filtered during

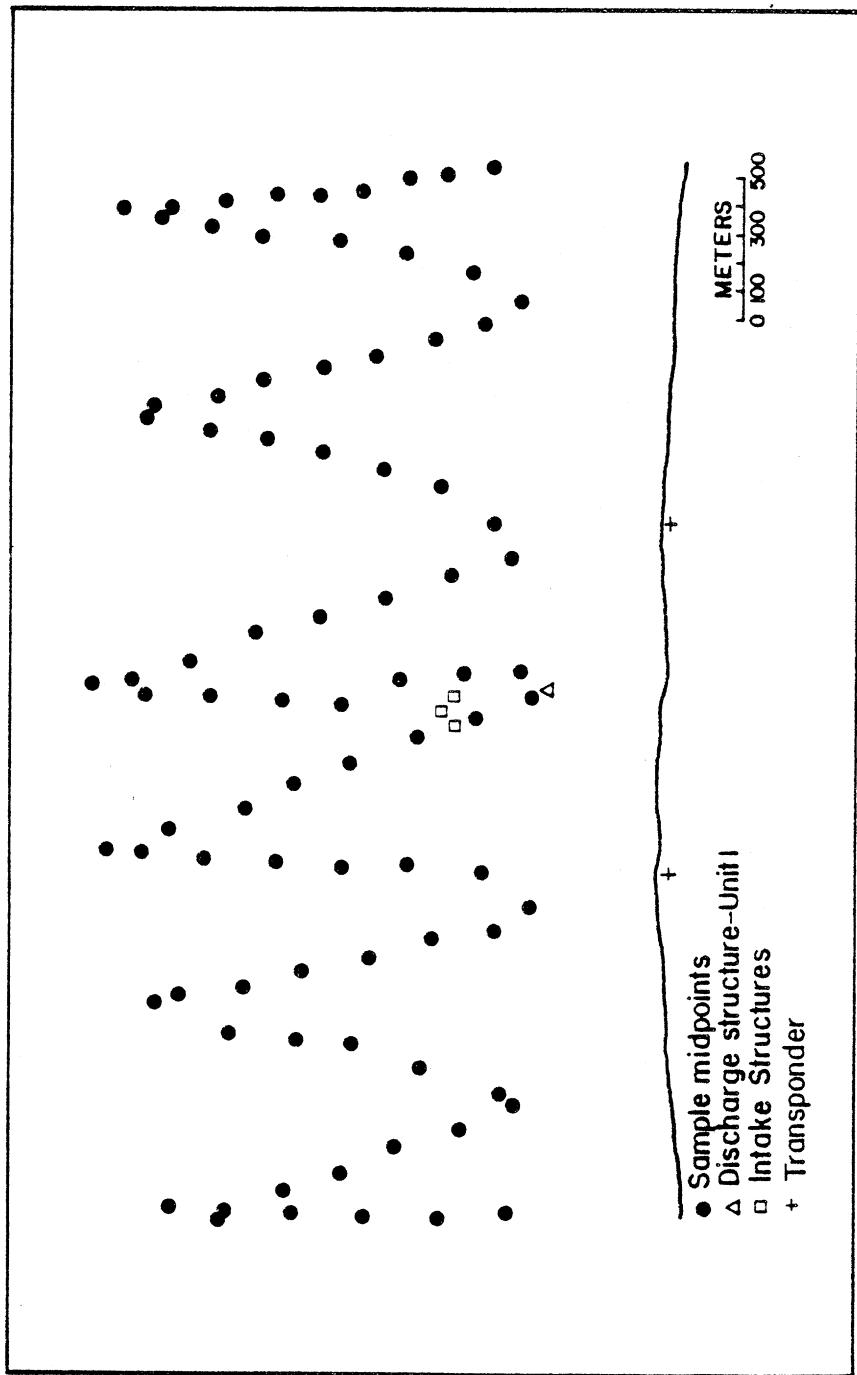


FIG. 57. Survey grid for the September 25, 1976 plume survey at 1 meter depth.

each sampling period. A thermistor located in the discharge pipe and connected to a time chart recorder gave continuous measurements of temperature with time. A Motorola-Mini-Ranger II was installed on board and two transponders were placed on shore. Readings from the Mini-Ranger were taken every minute to give ship location within meters. The lake was calm and wind speed was 5 mph from the north-north-west. Air temperatures were 17.2°C and slightly cooler than the ambient isothermal (17.8°C) water.

In the laboratory, samples were examined using the techniques described in Section 1. Adult copepods and cladocerans were identified to species, immature copepodites to genus, and nauplii to suborder.

Patterns of zooplankton density were examined using principal component analysis. The analysis was based on the variance-covariance matrix of the log-transformed data. All copepod and cladoceran taxa found at ten or more stations were used in the analysis. Correlations between log-transformed taxon density and the first and second principal components and temperature at the sample mid-point were calculated.

RESULTS

The thermally detectable ($\Delta T 0.1^{\circ}\text{C}$) plume was large and well-defined (Fig. 58). Although condenser-passed water was heated to 30.9°C from intake temperatures of 17.7 to 17.9°C , the maximum temperature recorded was 21.7°C , (directly over the discharge jets), indicating the rapid dilution which occurred in this region. Condenser-passed water represented approximately 30% of the water at this location.

The main body of the plume ($\Delta T 3^{\circ}\text{F}$, 1.7°C) extended over an area of approximately 0.1 km^2 and was bounded by the 19.5°C isotherm. Condenser-passed water accounted for less than 15% of the 1-m plume water beyond this isotherm. The area between the 19.5°C and the 17.9°C isotherms is designated the peripheral plume and was an area where dilution and cooling of the condenser-passed water occurred at a slower rate than in the main body of the plume. Ambient water to the south may have consisted of two or three different water bodies each with slightly different temperatures. The survey grid did not extend far enough to the north to detect ambient temperature water.

The current flow was primarily to the north as indicated by the compression of isotherms at the ambient-water peripheral-plume interface. The main body of the plume had a more westerly component of flow. This flow pattern was probably a result of the fact that the discharge jets consisted of two ports, one opening north and one opening west.

The zooplankton were numerically dominated by the cladoceran *Bosmina longirostris*. *Eubosmina coregoni* was the second most abundant cladoceran. The numerically dominant copepods were nauplii, *Cyclops bicuspidatus thomasi*,

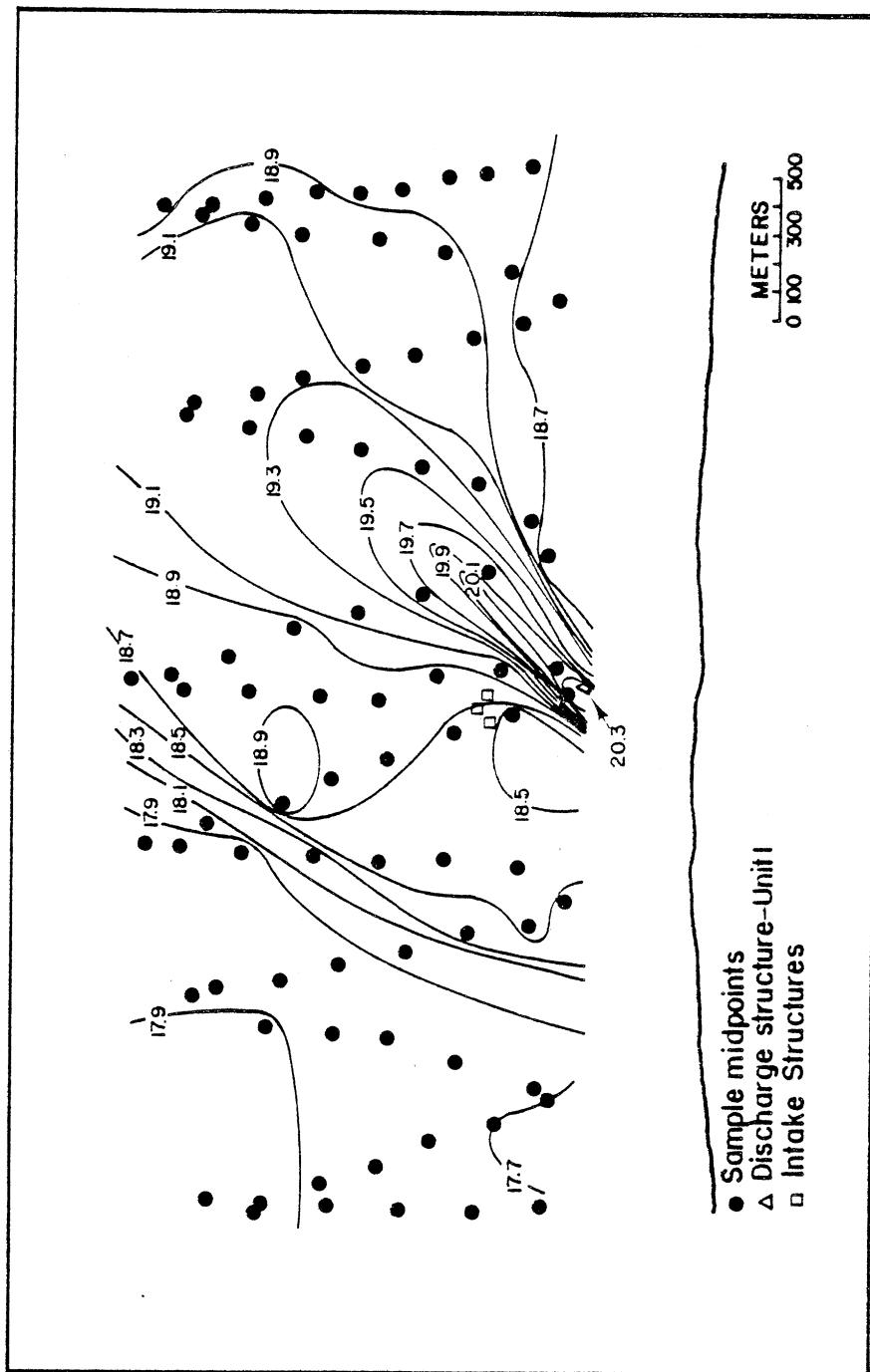


FIG. 58. The thermal plume at 1 meter depth on September 25, 1976.

Tropocyclops prasinus mexicanus, and Diaptomus spp. Benthic taxa such as Canthocamptus spp., Bryocamptus spp., Alona spp., Eury cercus lamellatus, and Macrothrix laticornis were collected in only a few samples and in low numbers.

Power plant operation produced alterations in the density distributions of most zooplankton. Taxa such as immature Cyclops spp., adult Cyclops bicuspidatus thomasi, immature Diaptomus spp., and Chydorus sphaericus (Fig. 59) occurred in high concentrations in the warmest waters of the plume and in lower concentrations in cooler waters. Zooplankton densities remained high up to several hundred meters from the discharge jets. However, zooplankton density isopleths did not parallel the isotherms and their locations varied with each taxon. Most isopleths had a northerly or westerly orientation.

Many taxa had irregular density distribution patterns. While nauplii and immature Eurytemora affinis copepodites tended to occur in higher concentrations in the warmer waters of the plume (Fig. 60) than in the peripheral plume, the area of elevated densities had even less correspondence with isotherm location than did the patterns exhibited by Cyclops spp. and Diaptomus spp. copepodites. In addition, nauplii and immature E. affinis copepodites occurred in high concentrations in ambient waters while Cyclops spp. and Diaptomus spp. concentrations were relatively low in this region. Daphnia retrocurva and Eubosmina coregoni (Fig. 60) exhibited a pattern similar to the nauplii and E. affinis patterns except that the area of elevated concentrations in the warmest waters of the plume was exceedingly small. This contrasts with the pattern exhibited by another cladoceran, Chydorus sphaericus, for which elevated concentrations in the plume extended over a distance of several hundred meters.

The distribution of Bosmina longirostris (Fig. 61) was unique, exhibiting an extreme amount of density variation. Densities within the ambient waters varied from 5,000 to 90,000/m³. Densities were lower in the plume (1,000 to 5,000/m³) with the area of lowest density located south of the warmest waters of the plume. There was very little correspondence between density isopleths and isotherms except at the boundary between ambient and peripheral plume water. Polypheus pediculus also occurred in higher concentrations in the ambient water than in the plume (Fig. 61) but there was no apparent area of low concentration centered on the warmest waters of the plume.

Principal component analysis of the log-transformed densities of 17 taxa were used to reveal community wide trends in zooplankton distributions. The first principal component (PC1) accounted for 32% of the total variance while the second principal component (PC2) accounted for an additional 14% of the variance. Ordination of stations by their first and second principal component values did not reveal any distinct station groups (Fig. 62). Therefore, the PC1 axis was divided into four equal parts, and the PC2 axis was divided into only two parts, since it accounted for only half the variance explained by PC1. The resulting eight station-groups were

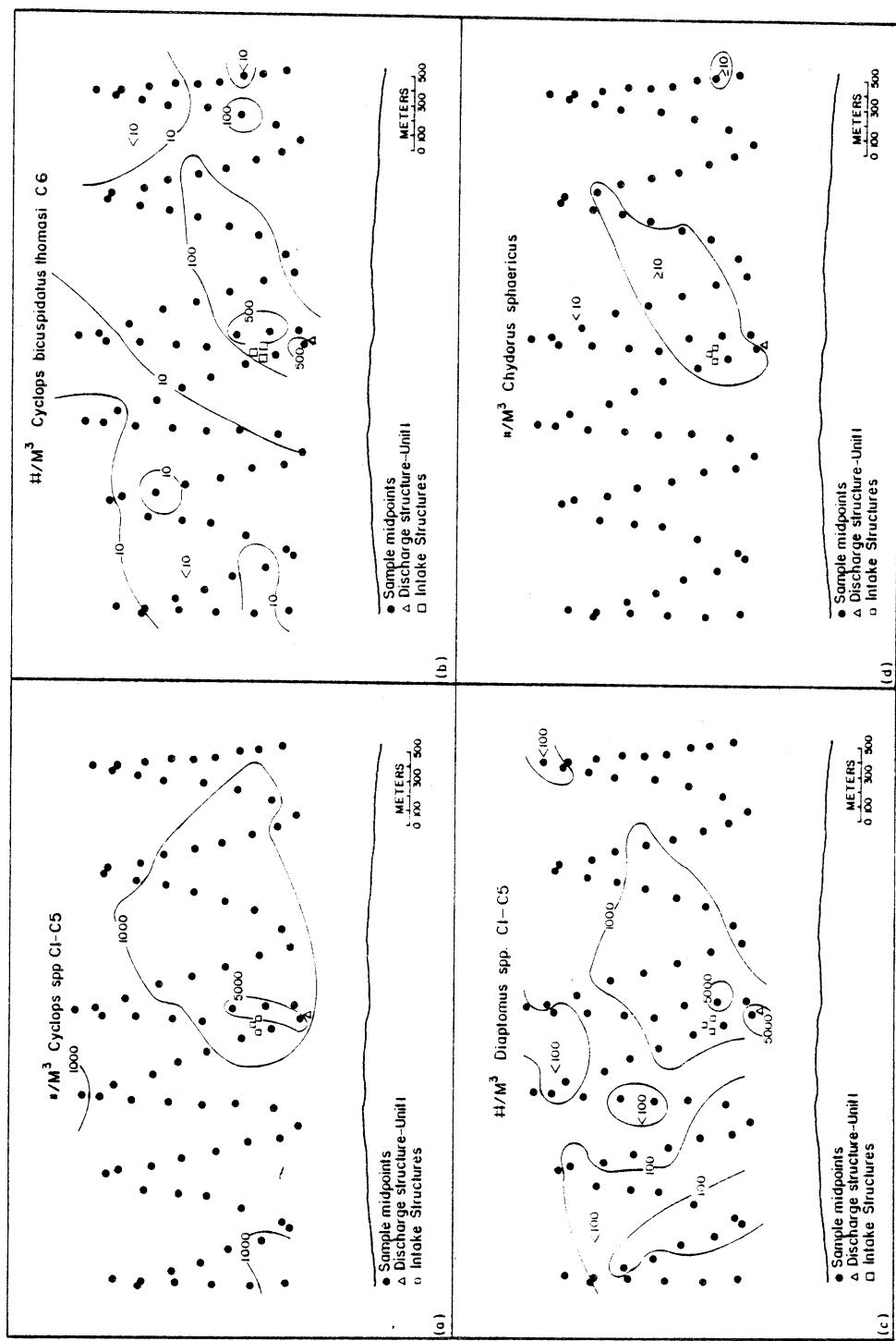


FIG. 59. The distribution of selected taxa reaching maximum densities in the thermal plume at 1 meter on September 25, 1976. a) Immature Cyclops spp., b) Cyclops bicuspidatus thomasi C6, c) Diaptomus spp. Cl-C5, and d) Chydorus sphaericus.

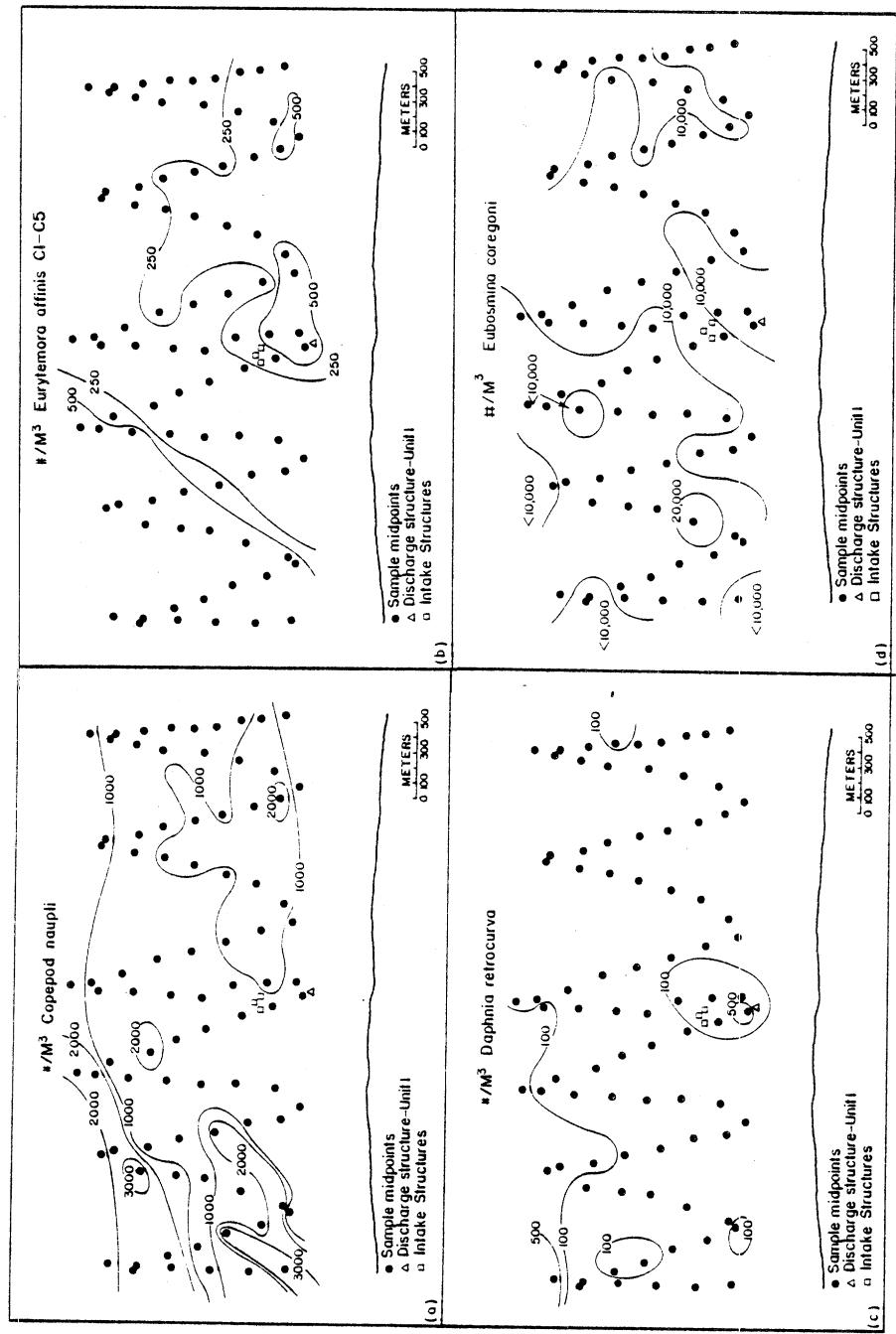


FIG. 60. The distribution of selected taxa reaching maximum densities in the thermal plume and in the ambient temperature water at 1 meter on September 25, 1976. a) Copepod nauplii, b) Eurytemora affinis C1-C5, c) Daphnia retrocurva, and d) Eubosmina coregoni.

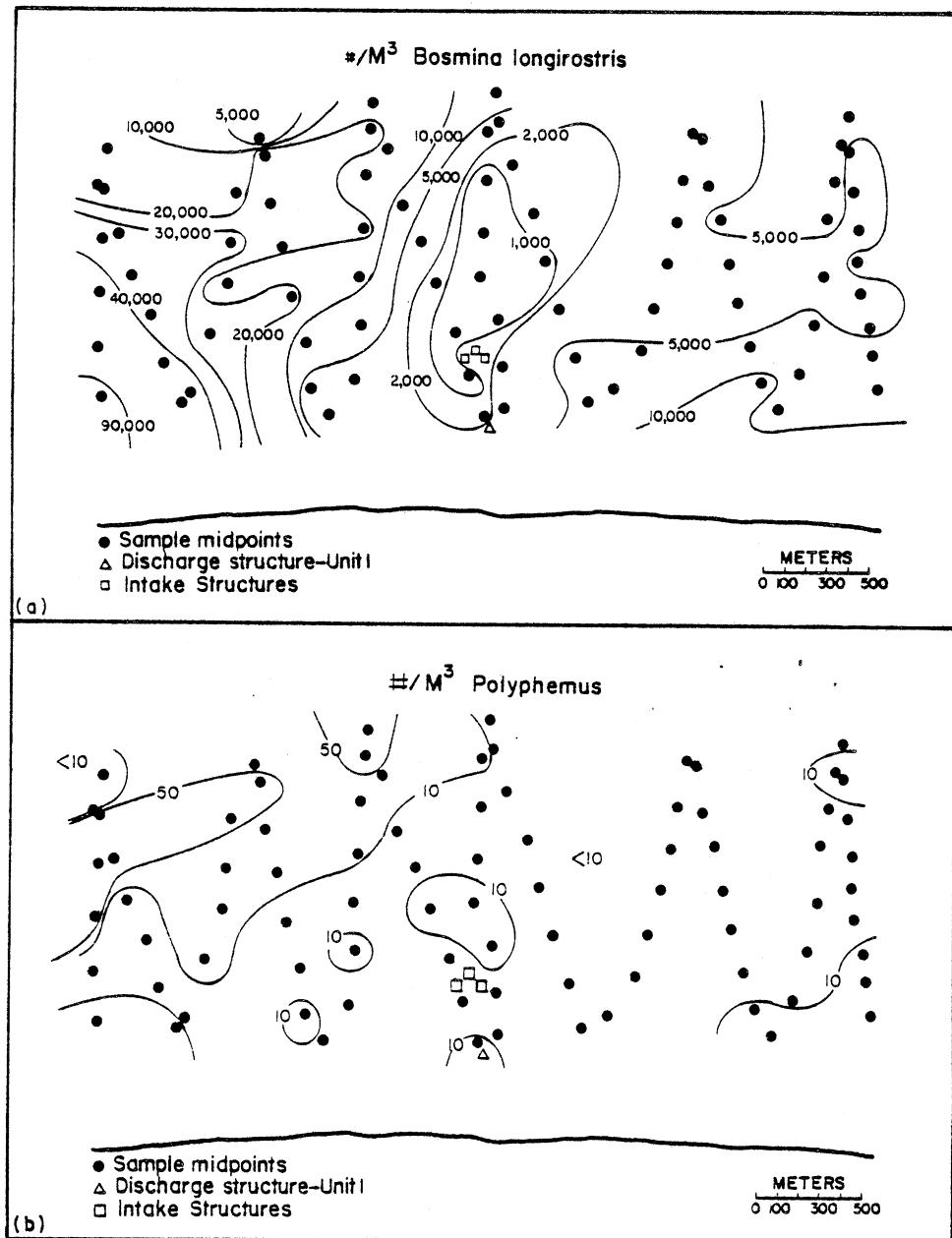


FIG. 61. The distribution of *Bosmina longirostris* and *Polyphemus pediculus* at 1 meter on September 25, 1976.

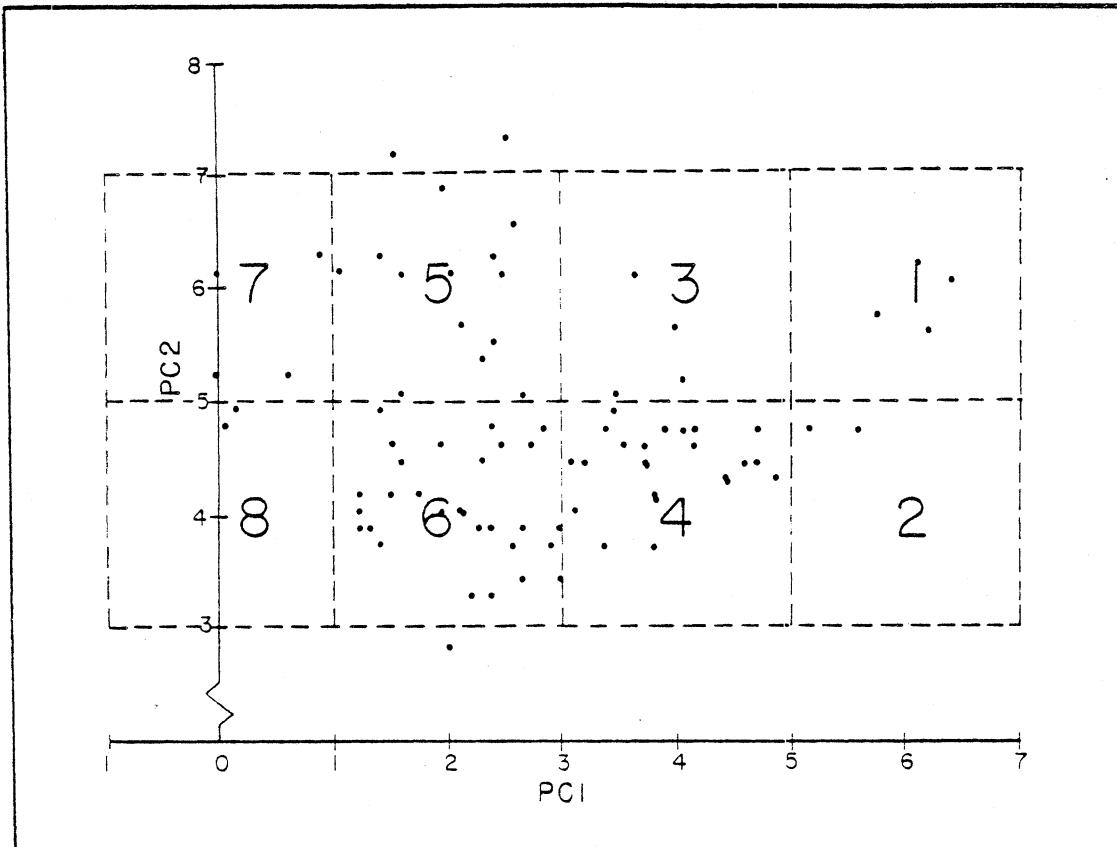


FIG. 62. Ordination of 1-meter plume survey stations by principal components 1 and 2.

identified on the plume grid and the three outlying stations were assigned to their nearest group. The boundaries of the resultant groups showed a strong correspondence to the boundaries between plume and ambient water (Fig. 63).

Zones 1 and 2 had the highest PC1 values and were located in the warmest waters of the plume. The $\Delta T 3^{\circ}F$ isotherm ($1.7^{\circ}C$) was located within these zones. Stations in zones 4 and 6 had lower PC1 values and were located primarily in the peripheral plume; the $18.8^{\circ}C$ isotherm ($\Delta T 1.0^{\circ}C$, $1.8^{\circ}F$) roughly separated the two zones. Most of the stations within the plume had low PC2 values. Four groups (3, 5, 7, 8) formed a complex association of stations in the ambient water to the south. Apart from the four stations in zone 3, all ambient water stations had low PC1 values. Most of the stations with high PC2 values were in ambient water.

Sorting of stations along the PC1 axis was strongly related to temperature; the correlation between station PC1 values and station midpoint temperature was $r=+0.63$. Taxa such as immature Diaptomus spp. copepodites which had high positive correlations with PC1 had moderately high correlations with temperature (Table 16) and occurred in maximum concentrations in the warmest waters of the plume (Fig. 64). Bosmina longirostris, which attained its highest densities in the cool ambient waters, exhibited the reverse trend with high negative correlations both with PC1 and temperature (Fig. 64). Taxa

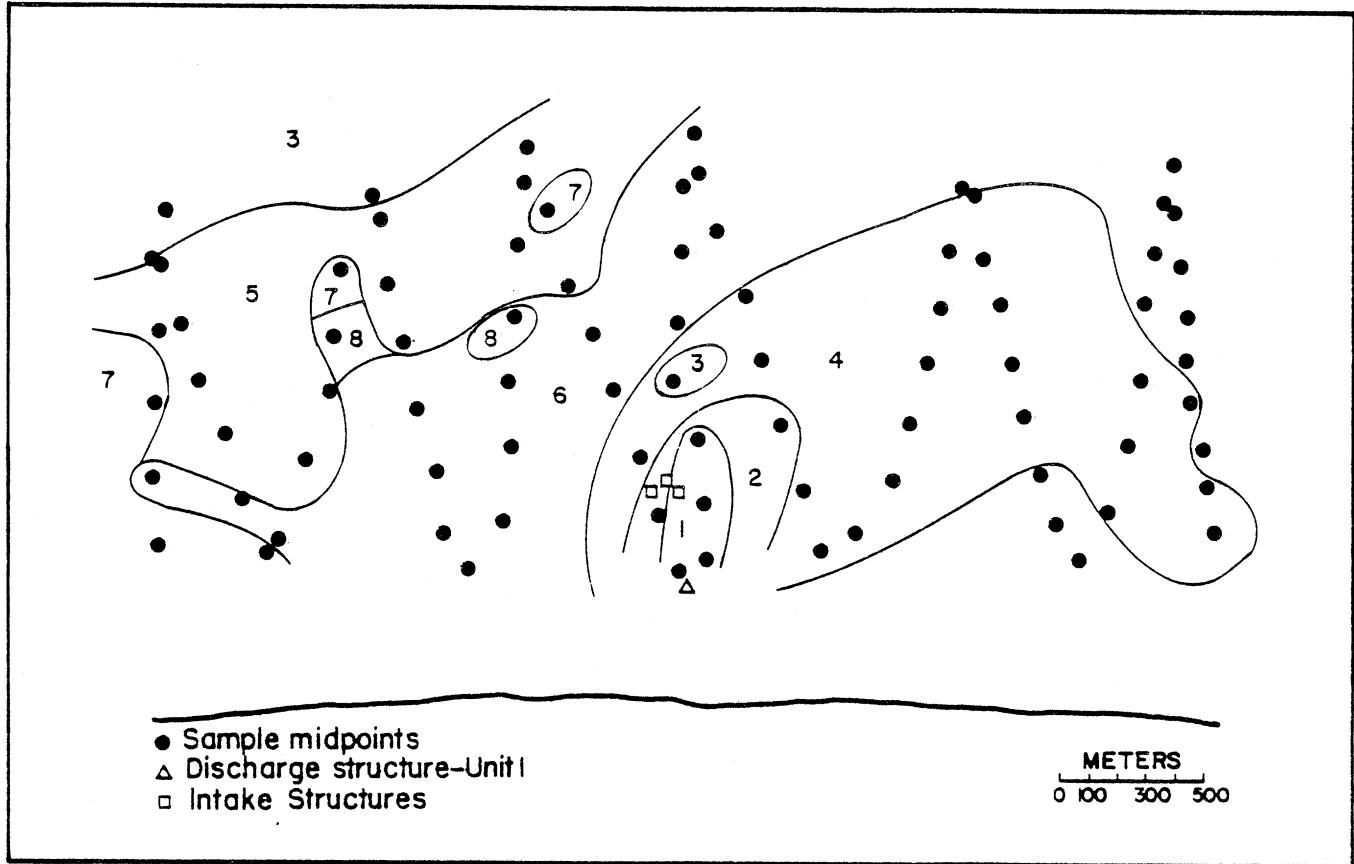


FIG. 63. Plume survey grid with the zones derived from PC 1 and PC 2.

such as Eubosmina coregoni, which occurred in high concentrations both in the warmest waters of the plume and in the ambient water, had lower correlations with PC1 and temperature (Fig. 64).

PC2 was negatively correlated with temperature ($r=-0.41$). Taxa with high correlations with PC2 tended to occur in relatively high concentrations in the ambient water; such taxa included Bosmina longirostris, Polypheus pediculus, Eurytemora affinis, Daphnia retrocurva, and nauplii. PC2 appears to be related to horizontal patchiness across the plume grid and the tendency for some taxa to be more abundant in the ambient water.

DISCUSSION

Temperature and zooplankton patchiness appear to be the two most important parameters contributing to the overall pattern of zooplankton distributions within the vicinity of the 1-m plume. Zooplankton distributions were strongly related to temperature in the thermal plume and to patchiness in the ambient water. Both factors were of importance in the peripheral plume.

The relationship between zooplankton density and temperature is of particular interest. Most taxa occurred in elevated concentrations in the

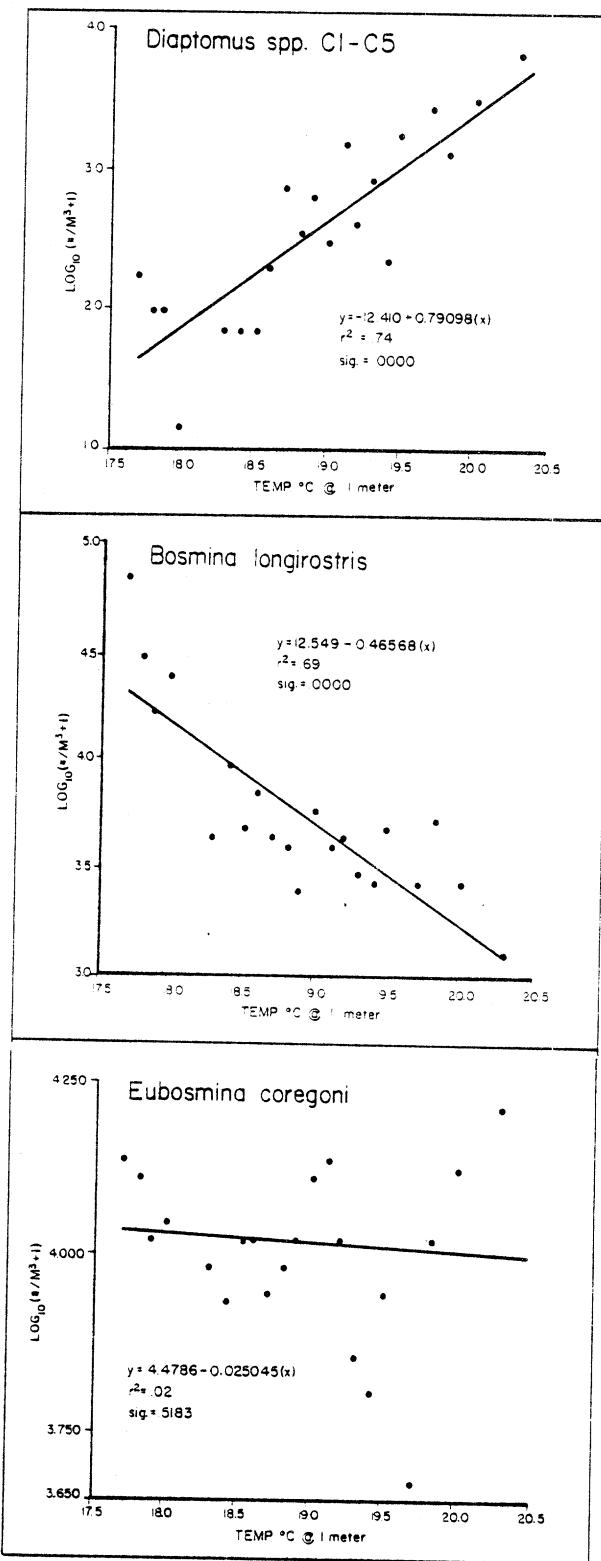


FIG. 64. Regression equations and scatter plots of mean density versus water temperature for Diaptomus spp. C1-C5, Bosmina longirostris, and Eubosmina coregoni. Densities are the \log_{10} transformed means ($\#/m^3$) each temperature, and water temperatures are taken at the sample midpoints.

TABLE 16. Linear correlation coefficients (r) between temperature at 1 meter, principal components 1 and 2, and the transformed ($\log_{10} x+1$) densities of 17 zooplankton taxa. All correlations with $r \geq .2146$ are significant at $p \leq .05$; and for $r \geq .2796$, $p \leq .01$.

Taxon	Correlation (r)		
	PC 1	PC 2	Temp @ 1m
<u>Diaptomus</u> spp. C1-C5	.8551	-.0586	.5820
<u>Cyclops bicuspis</u> <u>thomasi</u> C6	.8301	-.0717	.4687
<u>Cyclops</u> spp. C1-C5	.7420	.2313	.3940
<u>Diaphanosoma</u> spp.	.6924	.0918	.3738
<u>Bosmina longirostris</u>	-.6239	.4135	-.7349
<u>Chydorus sphaericus</u>	.6197	.0778	.4092
<u>Daphnia retrocurva</u>	.5648	.4977	.1847
<u>Epischura lacustris</u> C1-C6	.5473	-.2220	.4876
<u>Tropocyclops prasinus mexicanus</u> C1-C6	.4349	.4934	.0344
<u>Polypheus pediculus</u>	-.4157	.6256	-.4816
<u>Eubosmina coregoni</u>	-.3074	.3290	-.2975
<u>Leptodora kindtii</u>	.2277	.2654	.0629
<u>Daphnia galeata mendotae</u>	.1824	.1956	.0762
<u>Diaptomus minutus</u> C6	-.1702	.4643	-.3104
<u>Holopedium gibberum</u>	-.1118	.5605	-.1978
Copopod nauplii	-.1137	.4119	-.3520
<u>Eurytemora affinis</u> C1-C6	-.0351	.7268	-.5398
Temperature @ 1m	.6273	-.4132	----

warmer waters over the discharge jets and in decreasing concentration with plume mixing and dilution. This high concentration of zooplankton could have originated from populations at the 9-m depth contour which were drawn through the power plant and then discharged at 6 m. This assumes that zooplankton occurred in substantially higher concentrations at the 9 m depth contour than at the 6-m depth contour. Where such differences do exist, elevated concentrations of zooplankton have been detected in thermal plume discharge (Brauer et al. 1974). However, we have not observed large differences in zooplankton populations between the 6 and 9-m depth contours (Section 1) and zooplankton within this area and within the cooling waters were generally similar in abundance (Section 4). Therefore, gross differences in zooplankton population size between the intake and discharge structures do not appear to be an important factor contributing to the observed high concentrations of zooplankton over the discharge jets.

The most important factor producing high concentrations of zooplankton in the 1-m plume was probably related to mixing processes over the discharge jets. There, and up to several hundred meters away, water was strongly mixed and frequently was isothermal (Indiana and Michigan Power Company 1976). This mixing not only redistributed water but also zooplankton, so that normal zooplankton vertical distribution patterns were altered.

The vertical distribution of zooplankton has not been well studied in the nearshore area; however there appears to be a general trend for zooplankton to avoid the upper meter of the water column during daylight hours (Wells 1960). Unpublished vertical distribution data collected at 0.5, 2.5, 4.5, and 6 m at the 6-m depth contour a week prior to the plume study, and at 1.2, 2.9, 4.7, and 9.2 m, at a stations 11 km offshore during the morning of the plume study both show a general avoidance of the upper meter of the water column by zooplankton during daylight hours. Concentrations of most zooplankton taxa increased several fold below 1 m. A partial series of 3-meter plume samples collected after the 1-m plume mapping also indicated that most zooplankton increased in concentration below 1 m.

The vertical distribution of zooplankton and mixing processes can account for the observed distribution pattern in the plume. Assuming that zooplankton avoid the upper meter of the water column during the day, mixing processes over the discharge jets would transfer these deeper-living zooplankton to the surface, thus producing a local enrichment of zooplankton at 1 m. As the plume moved into the lake and mixed with cooler water, zooplankton densities gradually returned to normal due to dilution and possibly the downward migration of the zooplankton as plume flow became less turbulent. The concentration gradient within the plume and the areal extent of the elevated concentrations depends on vertical distribution patterns (particularly over the discharge jets), and on horizontal patchiness. Differences in these factors probably account for the fact that each zooplankton taxa had a unique pattern of increased concentrations within the plume and for the fact that zooplankton abundance isopleths did not strictly correspond with isotherms. The 1-m pattern for zooplankton distributions is also dependent upon the sampling time and possibly may be different at night when zooplankton migrate closer to the surface. Differences in zooplankton distributions within the plume probably also vary with depth both because zooplankton occur in different abundances in the deeper waters and because the plume generally decreases in size with depth.

Even after considering these factors, the density pattern for Bosmina longirostris remained puzzling. This taxon exhibited a large amount of variation in concentration in the ambient water and occurred in relatively low concentrations within the plume. The range in concentration was larger (360 to 97,100/m³) than previously encountered ranges for zooplankton densities within the inshore region. Since B. longirostris occurred in relatively low concentrations in the plume, this tends to suggest that this cladoceran was concentrated near the surface and that mixing processes over

the discharge jets reduced its 1-m concentrations. The partial 3-m plume map suggested that this taxon was less abundant at 3 m than at 1 m. However, limited vertical distribution data (unpublished) for this taxon show maximum populations at 5 m. In addition, within the plume, the area of lowest concentration was in the cooler plume water and south of the main direction of plume flow. The B. longirostris pattern thus appeared to be strongly affected by horizontal patchiness which was greater than its variation in density with depth. Other taxa also exhibited large amounts of horizontal patchiness but for some undetermined reason, this had less of an effect on their distribution pattern in the plume.

In summary, the plume study indicated that while there were detectable alterations in zooplankton distributions within the 1-m plume, these alterations were confined to a relatively small part of the 250 km² lake survey grid. The greatest disruptions in zooplankton distribution occurred within an approximate area of 0.1 km² (within the ΔT 1.7 C° isotherm) and were generally associated with increased concentrations of zooplankton relative to their densities a few hundred meters away from the discharge jets (peripheral plume). The localized increases in zooplankton concentration in the 1-m plume were due to mixing processes and redistribution of deeper-living zooplankton.

Such increases in zooplankton densities in the thermal plume could not be detected in our lake survey program where zooplankton samples were collected from the entire water column at each station and where station distances from the discharge jets were relatively large. The four closest stations, NDC .5-1, NDC .5-2, SDC .5-1, and SDC .5-2 were located over 800 m away from the discharge jets and were generally outside the area of greatest alterations in zooplankton densities at 1 m. Therefore, even if samples were collected at discrete depths in the lake survey study, these differences in zooplankton density could not have been adequately documented. Greater ranges in zooplankton densities were observed at a single depth (1 m) in the plume grid than have previously been encountered before in the inshore region, suggesting that zooplankton populations in this area have more complex distribution patterns than our lake survey data suggest.

CONCLUDING REMARKS

The general conclusion of the two-year study evaluating the impact of the Donald C. Cook Nuclear Power Plant on zooplankton populations in southeastern Lake Michigan is that Unit 1 operation did not adversely affect the maintenance of a "balanced, indigenous population in the discharge area." Cooling system design and site location were major factors minimizing damage to the zooplankton community. Large spatial and temporal variability in zooplankton abundances in the lake precluded detection of the small loss of zooplankton which occurred as a result of plant passage.

Mortalities due to plant passage were generally low and probably averaged only 1 or 2% for total zooplankton. Relatively low ΔT 's ($<12^{\circ}\text{C}$) and low discharge water temperatures ($<35^{\circ}\text{C}$) were of major importance in reducing the thermal stress zooplankton experienced during plant passage. However, zooplankton mortalities would approach 100% if the power plant were to increase the ΔT to 15 or 20°C or increase discharge water temperatures to 35 or 40°C . Subsurface discharge jets promoted rapid mixing and cooling of condenser passed water. This rapid cooling minimized thermal stress experienced by plume-entrained zooplankton. It is unlikely that short-term exposure (minutes) to temperatures 3 or 4°C above ambient (maximum ambient temperature 25°C) was lethal or sufficiently long to alter physiological rates to the extent that these rate changes resulted in increased or decreased populations in the thermal plume region.

Intense vertical mixing of water in the vicinity of the discharge jets prevented the loss (by sinking) from the water column of zooplankton killed by plant passage. Consequently, these losses could not be detected in samples collected in the vicinity of the discharge jets, which were preserved, and later examined in the laboratory. While significant settling of these dead zooplankton occurred a few hundred meters away from the discharge jets, condenser-passed water and zooplankton were so diluted in the lake water at these locations that even 100% loss of zooplankton due to condenser-passage could not be detected using current sampling methods. Lake currents transport zooplankton several kilometers a day (under average current velocities), constantly replenishing zooplankton standing stocks in the discharge area.

Power plant siting was a major factor in minimizing damage to the zooplankton community. Although substantial volumes of warm water were discharged into the lake, these volumes were an exceedingly small fraction of the total lake volume or the volume of the inshore region. Because of this, cooling (through mixing) was rapid. In contrast, plants on small lakes, harbors, or on rivers utilize substantial fractions of the water flowing past the plant site. In these situations, heat loss occurs relatively slowly and alterations in the zooplankton community have been observed (see Introduction).

While our two-year study has not observed any impact of power plant operation on the zooplankton community in thermal plume region, we have not concluded that damage has not occurred or will not occur. Rather we conclude that damage which has occurred is below our detection limits. There are several factors which warrant further concern.

First, while the Donald C. Cook Nuclear Power Plant utilizes relatively small volumes of lake water (in comparison to the total volume of the lake), continued increased power plant activity on the lake will alter this situation. Predictions by the Great Lakes Fishery Laboratory (1970), Sorge (1969), and Acres (1970) all suggest that intense power plant activity on large lakes has the potential for producing serious environmental disruptions in the aquatic community. Disruptions may occur either through detectable increases in lake temperature affecting the biota or by indirect routes which involve significant fractions of the aquatic community experiencing plant passage and consequent sublethal or lethal damage.

Our two-year study focused on the detection of localized effects of power plant operation on zooplankton in the thermal plume region. Within these spatial constraints, the emphasis clearly was on immediate, lethal effects of plant operation. Given the physical nature of the inshore region (rapid water exchange), the physiological characteristics of zooplankton (generation times ranging from days to months), and sampling programs designed to measure population size and mortality levels, we were limited to detecting short-term, localized effects. However, power plant operation may have long-term, lake wide effects on the aquatic community. This is an area which requires further investigation particularly with projected increased power plant activity on the lake. The pollution of Lake Michigan by phosphates, pesticides, and heavy metals was gradual and it was only after several years that the effects of these pollutants manifested themselves in changes in community structure. Similarly power plant operation may require a long period of time before the full impact of operation is detectable.

There are two major limitations with current monitoring programs. First, condenser passage studies focus on measuring mortality or the lethal effects of plant passage. Sublethal effects are currently ignored and consequently environmental changes which may occur as a result of biological interaction (i.e. indirect effects) are ignored. For example, the shift from a diatom to a blue-green algae community in eutrophic waters may occur when diatom productivity increases to such an extent that silica becomes limiting for diatoms (Schelske and Stoermer 1971). More information is required on basic zooplankton physiological processes and how they are affected by season, temperature, food levels, etc. Such information is generally available for a large number of fish species and for the phytoplankton but is lacking for the invertebrates.

Future studies should also be directed at gaining a better understanding of the factors affecting temporal and spatial variations in zooplankton

numbers. We have a moderate understanding of spatial variations in zooplankton numbers in the nearshore and have developed hypotheses which require testing. However, our understanding of temporal variations in zooplankton numbers except in a general seasonal pattern, is inadequate. Studies measuring zooplankton physiological rates, competition and predation would provide better understanding of factors affecting temporal and spatial variability in zooplankton populations. In addition, more frequent sampling, particularly in the warmer months of the year, would help quantify temporal variations in numbers.

In summary, we could not detect short-term, localized, lethal effects of power plant operation on the zooplankton community in the thermal plume region. Indirect, sublethal damage may be occurring which may, with time, affect the aquatic community over a relatively large area of the lake. The likelihood of such damage occurring increases with increased power plant activity on the lake. Future monitoring studies must be directed at gaining a better understanding of variations in zooplankton abundances, zooplankton interactions within the aquatic community, and the sublethal effects of plant passage and plume entrainment on zooplankton physiology.

REFERENCES

Acres, H.G., Ltd. 1970. Thermal inputs into the Great Lakes 1968-2000. Inland Waters Branch, Dept. of Energy, Mines, and Reservoirs. Canada Center for Inland Waters. Niagara Falls, Ontario.

Ayers, J.C. 1975. The phytoplankton of the Cook plant monthly minimal surveys during the preoperational years 1972, 1973, and 1974. Univ. Michigan, Great Lakes Res. Div. Spec. Rep. 59.

_____, D.C. Chandler, G.H. Lauff, C.F. Powers, and E.B. Hensen. 1958. Currents and water masses of Lake Michigan. Univ. Michigan, Great Lakes Res. Inst. Pub. 3.

_____, and E. Seibel. 1973. Study of aquatic macrophytes. In Benton Harbor Power Plant Limnological Studies. Part 13. Cook Plant preoperational studies, 1972. Univ. Mich., Great Lakes Res. Div. Spec. Rep. 44, pp. 169-177.

_____, A.E. Strong, C.F. Powers, and R. Rossmann. 1967. Benton Harbor Power Plant Limnological Studies. Pt. 2. Studies of local winds and alongshore currents. Univ. Michigan, Great Lakes Res. Div. Spec. Rep. 44.

Beeton, A.M. 1969. Changes in the environment and biota of the Great Lakes. In Eutrophication: Causes, consequences, correctives. Natl. Acad. Sci. pp. 150-187.

_____, and J.M. Barker. 1974. Investigation of the influence of thermal discharge from a large electric power station on the biology and nearshore circulation of Lake Michigan- Part A: Biology. Univ. Wisconsin-Milwaukee, Center for Great Lakes Studies, Spec. Rep. 18.

Brauer, G.A., W.M. Neill, and J.J. Magnuson. 1974. Effects of a power plant on zooplankton distribution and abundance near plant's effluent. Water Res. 8: 485-489.

Brooks, J.L. and S.I. Dodson. 1965. Predation, body size and composition of plankton. Science 150: 28-35.

Brown, L.A. 1926-27. Temperature characteristics for duration of an instar in cladocerans. J. Gen. Physiol. 10: 111-119.

_____, and W. J. Crozier (1927-1928). The rate of killing of cladocerans at higher temperatures. J. Gen. Physiol. 11: 25-36.

Carpenter, E.J., B.B. Peck, and S.J. Anderson. 1974. Survival of copepods passing through a Nuclear Power Station on Northwestern Long Island Sound, USA. Marine Biol. 24: 49-55.

Comita, G.W. 1968. Oxygen consumption in Diaptomus. Limnol. Oceanogr. 13: 51-57.

Conover, W.J. 1971. Practical Nonparametric Statistics. Wiley, New York.

Davies, R.M. and L.M. Jensen. 1974. Effects of entrainment of zooplankton in three mid-Atlantic power plants. Electric Power Research Institute. Palo Alto, California. Report no. 10.

Deevey, E.S. and G.B. Deevey. 1971. The American species of Eubosmina Seligo (Crustacea, Cladocera). Limnol. Oceanogr. 16: 201-208.

Drost-Hansen, W. 1969. Allowable thermal pollution limits - a physico-chemical approach. Ches. Sci. 10: 281-288.

Edmondson, W.T. (ed). 1959. Fresh-water Biology. 2nd ed. Wiley.

Eiler, H.O. and J.J. Delfino. 1974. Limnological and biological studies of the effects of two modes of open-cycle nuclear power station discharge on the Mississippi River (1969-73). Water Res. 8: 995-1005.

Engel, R.A. 1962. Eurytemora affinis, a calanoid copepod new to Lake Erie. Ohio J. Sci. 62: 252.

Evans, M.S. 1975. The 1974 preoperational zooplankton investigations relative to the Donald C. Cook nuclear plant. Univ. Michigan, Great Lakes Res. Div. Spec. Rep. 58.

_____ and B. E. Hawkins. 1975. An examination of the spatial heterogeneities in the distribution of zooplankton during the major survey cruises. In M.S. Evans. The 1974 preoperational zooplankton investigations relative to the Donald C. Cook nuclear plant. Univ. Michigan, Great Lakes Res. Div. Spec. Rep. 58. pp. 70-96.

_____ and J.A. Stewart. 1977. Epibenthic and benthic microcrustaceans (copepods, cladocerans, ostracods) from a nearshore area in southeastern Lake Michigan. Limnol. Oceanogr. 22: 1059-1066.

Galbraith, M.G., Jr. 1967. Size-selective predation on Daphnia by rainbow trout and yellow perch. Trans. Amer. Fish. Soc. 96: 1-10.

Gannon, J.E. 1972. A contribution to the ecology of zooplankton Crustacea of Lake Michigan and Green Bay. Univ. Wis. Cent. Great Lakes Stud.

Great Lakes Fishery Laboratory. 1970. Physical and ecological effects of waste heat on Lake Michigan. U.S. Dept. Interior, Fish and Wildlife Service, Ann Arbor, Michigan.

Green, J. 1956. Growth, size and reproduction in Daphnia (Crustacea, Cladocera). Proc. Zool. Soc. London 126: 173-204.

Hall, D.J. 1964. An experimental approach to the dynamics of a natural population of Daphnia galeata mendotae. Ecology 45: 94-112.

Heinle, D.R. 1969. Temperature and zooplankton. Ches. Sci. 10: 186-209.

Hjulstrom, F. 1939. Marine sedimentation. In Sverdrup, H.U., M.U. Johnson, and R.M. Fleming, eds., The Oceans. Prentice-Hall, Inc. p. 961.

Icanberry, J.W. and R.W. Richardson. 1973. Quantitative sampling of live zooplankton with a filter pump system. Limnol. Oceanogr. 18: 333-335.

Indiana & Michigan Electric Company. Donald C. Cook Nuclear Plant, Units 1 and 2. 1975. Plan of study and demonstration concerning thermal discharges at the Donald C. Cook nuclear plant. Submitted to the Michigan Water Resources Commission.

_____. 1976. Report of the performance of thermal plume areal measurements. Vols. 1 and 2.

Industrial Bio-Test laboratories, Inc. 1974a. Thermal tolerance limit determinations for Lake Michigan zooplankton. Project XVII-B IBT no. 643-01862. July 1972 to March 1973. Report to Commonwealth Edison Company.

_____. 1974b. Environmental monitoring in Lake Michigan near Zion and Waukegan generating stations. January 1972 through December 1972. Vol 2. Report to Commonwealth Edison Company.

_____. 1974c. Operational monitoring in Lake Michigan near Zion station. July 1973 through June 1974. Vol 2. Report to Commonwealth Edison Company.

_____. 1975. Operational environmental monitoring program of Lake Michigan near the Kewaunee nuclear power plant: Chemical and biological studies. Fourth annual report. January to December 1974. Report to Wisconsin Public Service Corporation. Wisconsin Power and Light Company. Madison Gas and Electric Company.

Janssen, J. 1976. Feeding modes and prey size selection in the alewife (Alosa pseudoharengus). J. Fish. Res. Board Can. 33: 1972-1975.

Johnson, M.G. and R.O. Brinkhurst. 1971. Benthic community metabolism in Bay of Quinte and Lake Ontario. J. Fish Res. Board Can. 31: 1715-1725.

Johnston, E.M. 1973. Effect of a thermal discharge on benthos populations: statistical methods for assessing the impact of the Cook Nuclear Plant. Benton Harbor Limnological Studies, Part 18. Univ. Michigan, Great Lakes Res. Div. Spec. Rep. 44.

Jude, D.J., F.J. Tesar, J.A. Dorr III, T.J. Miller, P.J. Rago, and D.J. Stewart. 1975. Inshore Lake Michigan fish populations near the Donald C. Cook Nuclear Power Plant. Univ. Michigan, Great Lakes Res. Div. Spec. Rep. 52.

Krezoski, J.R. 1969. Some effects of power plant waste heat discharge on the ecology of Lake Michigan. Benton Harbor Plant Limnological Studies. Part 3. Univ. Michigan, Great Lakes Res. Div. Spec. Rep. 44.

Limnetics, Inc. 1975. An environmental study of the ecological effects of thermal discharge from the Point Beach Nuclear Plant. Nov. 1973 through October 1974. Annual Report No. 2. Vol. 2. Report to the Wisconsin Power Company and Wisconsin Michigan Power Co.

_____. 1976. An environmental study of the ecological effects of thermal discharge from the Point Beach Nuclear Plant. Nov. 1974 through October 1975. Annual Report no 3. Report to the Wisconsin Power Company and Wisconsin Michigan Power Co.

Lovegrove, T. 1966. The determination of the dry weight of plankton and the effects of various factors on the values obtained. In Some contemporary studies in marine science. Edited by H. Barnes. Allen and Unwin, London. pp. 429-467.

MacArthur, J.W. and W.H.T. Baillie. 1929a. Metabolic activity and duration of life. 1. Influence of temperature on longevity in Daphnia magna. J. Exp. Zool. 53: 221-242.

_____. and _____. 1929b. Metabolic activity and duration of life. 2. Metabolic rates and their relation to longevity in Daphnia magna. J. Exp. Zool. 53: 243-268.

Markowski, S. 1962. Faunistic and ecological investigations in Cavendish Dock, Barrow-in-Thames. J. Anim. Ecol. 31: 43-51.

McLaren, I.A. 1974. Demographic strategy of vertical migration by a marine copepod. Amer. Nat. 108: 91-102.

McMahon, J.W. and A.E. Docherty. 1975. Effects of heat enrichment on species succession and primary production in freshwater plankton. In Environmental effects of cooling systems at nuclear power plants. International Atomic Energy Agency, Vienna. pp. 529-546.

Morsell, J.W. and C.R. Norden. 1968. Food habits of the alewife Alosa pseudoharengus (Wilson) in Lake Michigan. In Proc. 11th Conf. Great Lakes Res., pp. 96-102. Internat. Assoc. Great Lakes Res.

Mozley, S.C. 1973. Study of benthic organisms, In J.E. Ayers and E. Seibel. Benton Harbor Power Plant Limnological Studies Part 13. Univ. Michigan, Great Lakes Res. Div. Spec. Rep. 44. pp. 178-249.

_____. 1974. Preoperational studies of benthic macroinvertebrates in Lake Michigan near the Cook nuclear plant. In J.C. Ayers and E. Seibel. The biological, chemical, and physical character of Lake Michigan in the vicinity of the Donald C. Cook Nuclear Plant. Univ. Michigan, Great Lakes Res. Div. Spec. Rep. 51. pp. 5-138.

Naylor, E. 1965. Effects of heated effluent upon marine and estuarine organisms. Adv. Mar. Biol. 3: 63-103.

Nebeker, A.V. 1976. Survival of Daphnia, crayfish, and stoneflies in air-supersaturated water. J. Fish. Res. Board Can. 33: 1208-1212.

Parker, J.I., H.L. Conway, and E.M. Yaguchi. 1977. Dissolution of diatom frustules and recycling of amorphous silicon in Lake Michigan. J. Fish Res. Board Can. 34: 545-551.

Patalas, K. 1970. Primary and secondary production in a lake heated by thermal power plant. Proc. Inst. Sci. 9: 267-271.

_____. 1972. Crustacean plankton and the eutrophication of the St. Lawrence Great Lakes. J. Fish Res. Board Can. 29: 1451-1462.

Pennak, R.W. 1963. Species identification of the freshwater cyclopoid Copepoda of the United States. Trans. Amer. Microsc. Soc. 82: 353-359.

Pratt, D.M. 1943. Analysis of population development in Daphnia at different temperatures. Biol. Bull. 85: 116-140.

Reeve, M.R. 1970. Seasonal changes in the zooplankton of south Biscayne Bay and some problems of assessing the effects on the zooplankton of natural and artificial thermal and other fluctuations. Bull. Mar. Sci. 20: 894-921.

Reif, C.B. and D.W. Tappa. 1968. Selective fish predation: smelt and cladocerans in Harvey Lake. Limnol. Oceanogr. 11: 437-438.

Robertson, A., C.W. Gehrs, B.D. Hardin, and G. Hunt. 1974. Culturing and ecology of Diaptomus clavipes and Cyclops vernalis. United States Environmental Protection Agency. Report EPA-660/3-74-006.

Ross, F.F. and J.W. Whitehouse. 1973. Cooling towers and water quality. Water Res. 7: 623-631.

Rossmann, R. 1975. Chemistry of nearshore surficial sediments from southeastern Lake Michigan. Univ. Michigan, Great Lakes Res. Div. Spec. Rep. 57.

Roth, J.C. 1973. Study of the zooplankton. In J.C. Ayers and E. Seibel. Benton Harbor Limnological Studies. Pt 13. Univ. Michigan, Great Lakes Res. Div. Spec. Rep. 44. pp. 77-168.

Schelske, C.L. and E. F. Stoermer. 1971. Eutrophication, silica depletion and predicted changes in algal quality in Lake Michigan. Science 173: 423-424.

Seigel, S. 1956. Nonparametric Statistics for the Behavioral Sciences. McGraw-Hill. New York.

Sorge, E.V. 1969. The status of thermal discharge east of the Mississippi River. Ches. Sci. 10: 131-138.

Stewart, J. 1974. Lake Michigan zooplankton communities in the area of the Cook nuclear plant, In J.C. Ayers and E. Seibel. The biological, chemical, and physical character of Lake Michigan in the vicinity of the Donald C. Cook Nuclear Plant. Univ. Michigan, Great Lakes Res. Div., Spec. Rep. 51. pp. 211-332.

Texas Instruments Incorporated. 1975. 1974-1975 Annual Report. Bailly nuclear site 1 encompassing April 1974- February 1975. Report to Northern Indiana Public Service Co.

United States Atomic Energy Commission. 1973. Final environmental statement related to the operation of the Donald C. Cook nuclear power plant. Units 1 and 2. Indiana and Michigan Electric Company and Indiana and Michigan Power Company. Docket nos. 50-315 and 50-316.

United States Department of the Interior, Federal Water Pollution Control Administration. 1968. Water quality investigations, Lake Michigan basin: Physical and chemical quality conditions. FWPCA, Chicago.

United States Environmental Protection Agency. 1974. Proposed Guideline for Administration of the 316(a) regulations. (draft, April 18, 1974). Director, Water Planning Division (AW-454).

Wells, L. 1960. Seasonal abundances and vertical movements of plankton crustacea in Lake Michigan. U.S. Fish Wildl. Serv., Fish. Bull. 60: 343-364.

— 1968. Seasonal depth distribution of fish in southeastern Lake Michigan. U.S. Fish. Wildl. Serv., Fish. Bull. 67: 1-15.

— 1970. Effects of alewife predation on zooplankton populations in Lake Michigan. Limnol. Oceanogr. 15: 556-565.

Wheeler, E.H., Jr. 1967. Copepod detritus in the deep sea. Limnol. Oceanogr. 12: 697-702.

Whitehouse, J.W. 1971. Some aspects of the biology of Lake Trawsfynydd: a power station cooling pond. Hydrobiol. 38: 253-288.

Zhitjenjowa, T.S. and J.I. Nikanorow. 1972. Der Einfluss des vom Konakowschen Warmekraftwerk abfliebenden Warwassers auf die biologischen Prozesse im Iwanikowo-Stuassee. Verh. Internat. Verein. Limnol. 18: 833-836.